The Pleistocene glaciations in the Dutch sector of the North Sea. A synthesis of sedimentary and seismic data

Cees Laban
Marine Geological Advice

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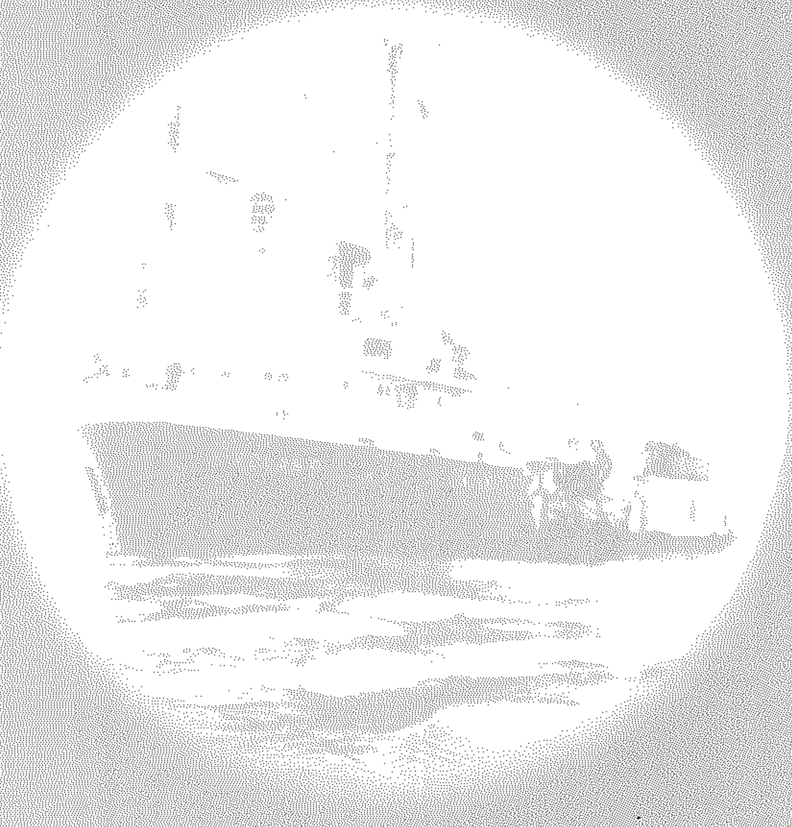

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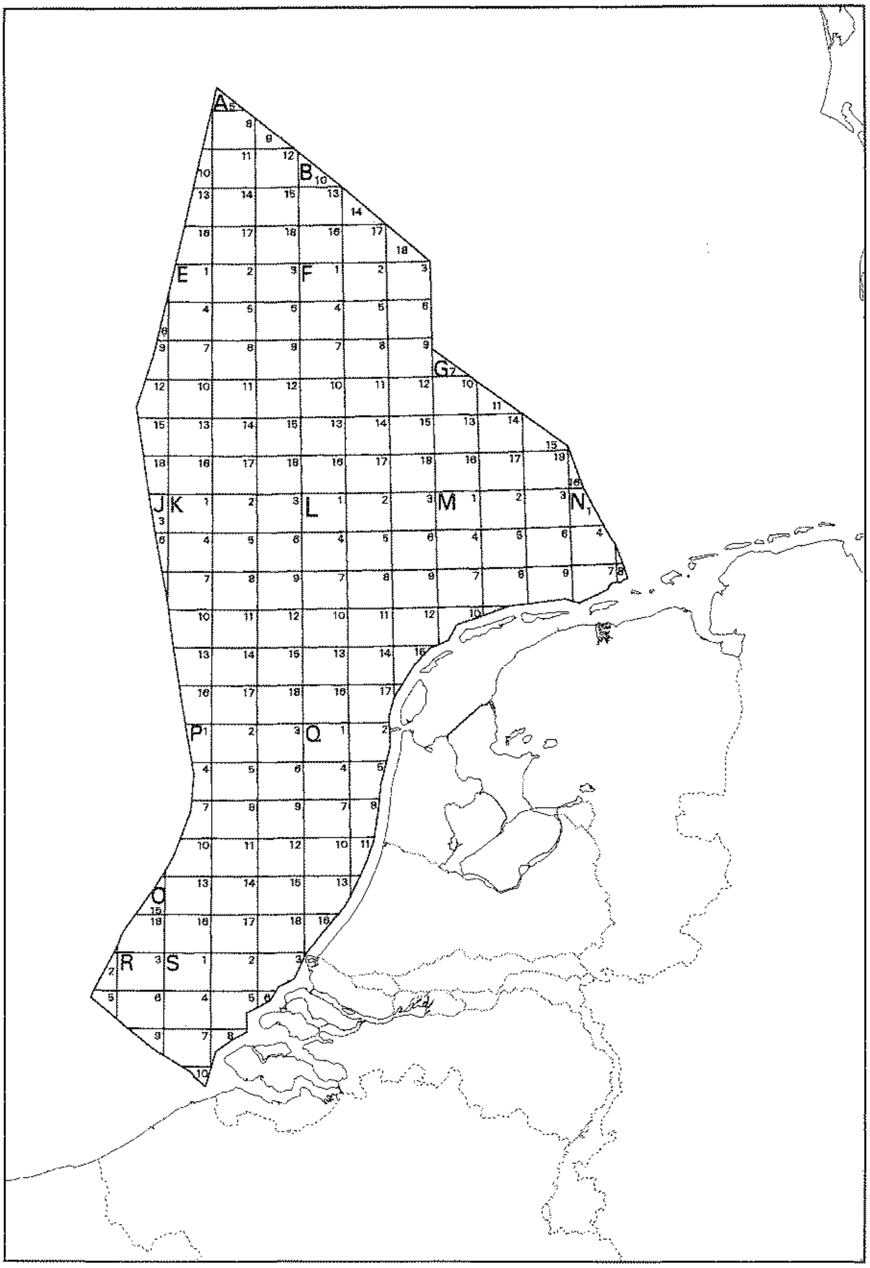

Dutch sector of the North Sea with licence blocks for oil and gas exploration.

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A synthesis of sedimentary and seismic data

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A synthesis of sedimentary and seismic data

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SAMENVATTING

Hoofdstuk 1

Als introductie voor dit proefschrift is een recente publikatie (Cameron et al., 1993) gebruikt om een inzicht te geven in de ontwikkelingsgeschiedenis van het Noordzeebekken van het pre-Perm tot het Holoceen.

Hoofdstuk 2

In dit hoofdstuk wordt een korte beschrijving gegeven van de bij het geologisch onderzoek op zee gebruikte technieken voor de uitvoering van diepere boringen en korte ongeroerde kernen en de methoden van bemonstering. Dit om een inzicht te geven in de typen monsters die zijn verzameld. Voorts worden de gebruikte seismische systemen en de hierbij optredende problemen en voordelen van deze methoden besproken. Tevens wordt een korte beschrijving gegeven van de macro- en micropaleontologische, mineralogische en petrologische analyses die zijn gebruikt.

Hoofdstuk 3

Op slechts enkele lokaties zijn glacigene of 'koude' mariene en fluviatiele sedimenten gerelateerd aan de Vroegpleistocene glaciaties gevonden in boringen in respectievelijk het Britse, Nederlandse, Duitse en Noorse deel van de Noordzee. In het Nederlandse deel dateren de oudste aanwijzingen voor glaciale invloed vermoedelijk uit de Tiglien C4c fase. De sedimenten waarin de aanwijzingen zijn aangetroffen bestaan uit stugge mariene klei van de IJmuiden Ground Formatie en zijn in twee boringen aangetroffen. Sedimenten uit het koude Eburonien zijn vermoedelijk aangetroffen in een van de diepere boringen. Ze bestaan uit pro-delta en deltafront-afzettingen en behoren tot de Winterton Shoal Formatie. Fluviatiele afzettingen van de Elbe en Weser waarin indicaties zijn gevonden voor koude omstandigheden tijdens het Menapien, zijn aangetroffen in twee boringen. De oudste glacigene afzettingen zijn aangetroffen in een diepere boring nabij de Doggersbank en zijn vermoedelijk gevormd tijdens het Cromerien A of B Glaciaal. Voorts zijn 'koude' mariene sedimenten uit het Cromerien aangetroffen in een meer oostelijk uitgevoerde boring. De correlatie van de 'koude' afzettingen tussen de verschillende boringen is niet mogelijk door de grote afstanden tussen de boringen en het feit dat de meeste boringen slechts sedimenten uit één koude tijd bevatten.

Hoofdstuk 4

In tegenstelling tot de voorgaande koude tijden komen glaciale sedimenten en verschijnselen, geproduceerd tijdens het Middenpleistocene Elsterien, veelvuldig voor. Tijdens deze glaciatie vond over grote gebieden erosie plaats. Een probleem tijdens het onderzoek vormt de diepteligging van de sedimenten tussen de subglaciale dalen en de schouders van deze dalen en het bereik van de 3.5 kHz en laag-frequente seismische systemen. Deze komen namelijk voor in het in hoofdstuk 2 besproken 'seismisch hiaat' dat bij gebruik van de beide systemen ontstaat. Om dit te overbruggen is meer aandacht besteed aan de tot ongeveer 100 m diepe boringen die tot in de afzettingen uit het Elsterien reiken. Tijdens het Laat-Elsterien is een zone met een patroon van diepe subglaciaal gevormde dalen ontstaan tussen voornamelijk 53°N en 55°N. Deze zone loopt van de Ierse Zee tot in Polen. Het diepe deel van de opvulling van deze dalen is alleen beschreven aan de hand van seismische opnamen.

Het bovenste deel van de opvulling van deze dalen is glaciomarien, dit in tegenstelling tot vroegere aannamen waarin werd uitgegaan van een glaciolacustriene opvulling, de Swarte Bank Formatie. De overgang van de arctische condities naar de boreale van het Holstein Interglaciaal ging geleidelijk. Er blijkt geen hiaat te bestaan tussen de sedimentatie aan het eind van het Elsterien en het Holsteinien, zoals werd aangenomen. In tegenstelling tot de twee latere, Midden- en Laatpleistocene glaciaties, zijn er vrijwel geen afzettingen van keileem gevonden.
Langs de zuidrand van de ijsuitbreiding tijdens het Elsterien zijn enkele tongbekkens aanwezig waarlangs deformatiestrukturen veroorzaakt door ijsdruk zijn waargenomen. Slechts plaatselijk zijn periglaciale afzettingen gevonden, afgezet voorafgaand aan de vergletsjeringsfase. Deze sedimenten worden tot de Middelrug Formatie gerekend en bereiken dikten tussen ca. 4 m en 6 m. Aan het eind van de glaciatie zijn geen periglaciale afzettingen meer gevormd. Onder mariene omstandigheden in dit deel van de Noordzee werd klei afgezet in onder meer de gedeeltelijk open subglaciale dalen van het Elsterien.

Hoofdstuk 5

In tegenstelling tot de sedimenten en verschijnselen van de voorgaande glaciaties, liggen de meeste afzettingen uit het Saalien binnen het bereik van de 3.5 kHz systemen. Hierdoor kon de geometrie van de periglaciale, glaciolacustriene en glacigene afzettingen meer gedetailleerd in kaart worden gebracht.
In het Nederlands deel van de Noordzee zijn tot nu toe alleen periglaciale sedimenten gevonden die zijn afgezet voorafgaand aan de Laat-Saalien-glaciatie. Ze bestaan uit zeer fijne tot fijne zanden behorend tot de Tea Kettle Hole Formatie. De formatie komt hoofdzakelijk in het noordelijk deel van de Nederlandse sector voor. De dikte varieert tussen 1 en 10 m. In een diep dal zijn, onder een Laat-Saalien-keileem, mariene afzettingen aangetroffen die mogelijk zijn gevormd onder arctische tot boreale omstandigheden tijdens een Vroeg-Saalian interstadiaal. Het Scandinavische ijs drong de Noordzee in het Laat-Saalien binnen en strekte zich uit over het oostelijk deel van de Nederlandse Noordzee. Stugge tot zeer stugge glaciolacustriene kleien van de Cleaver Bank Formatie komen hoofdzakelijk voor in het noordelijk en noordwestelijk deel van de Nederlandse sector en bereiken over het algemeen dikten tussen 4 m en 6 m. Keilemen van de Borkumriff Formatie komen voor ten noorden van de Nederlandse kust. Gebaseerd op hun lithologie zijn er twee verschillende keilemen onderscheiden. De dikte van de keileem varieert tussen <1 en 10 m. Fijne tot middelkorrelige fluvioglaciale zanden van de Molengat Formatie zijn slechts plaatselijk aangetroffen. De verbreiding is vermoedelijk veel groter geweest, maar de afzettingen zijn marien omgewerkt tijdens de Eemientransgressie. De Eemien-sedimenten bevatten vaak Scandinavisch grind. De voorkomens van subglaciale dalen uit het Saalien vormen nog steeds een probleem doordat het diepe deel van deze dalen buiten het bereik van de 3.5 kHz seismische systemen ligt. De dalen hebben veel geringere dimensies dan de dalen uit het Elsterien en zijn grotendeels opgevuld met mariene afzettingen uit het Eemien. Hierdoor is het moeilijk onderscheid te maken tussen dalen die tijdens de Eem-transgressie zijn gevormd en de Saalien-dalen.
Tongbekkens met deformatiestructuren langs de randen zijn op twee locaties aangetroffen. In het noordelijk deel van de Nederlandse sector zijn vermoedelijk zogenoemde icings aangetroffen. Voorkomens van glaciaal grind aan het zeebodemoppervlak, behorend tot de Indefatigable Grounds Formatie, bevatten aanwijzingen voor Scandinavische herkomst. Door het ontbreken van zogenoemde Hesemann-tellingen aan Saale-grind in de Noordzee, behorend tot de Indefatigable Grounds Formatie, en het ontbreken van oriëntaties van lengte-assen aan grind in de keilemen, is het niet goed mogelijk gedetailleerde uitvloeiingsrichtingen van het

landijs te geven. De aanwijzingen voor afwezigheid van Brits ijs in de zuidelijke Noordzee tijdens het Saalien, worden besproken.
Gebaseerd op de glaciale sedimenten en andere glaciale fenomenen, kon een meer gedetailleerde reconstructie van het maximale uitbreiding van het landijs worden gemaakt.

Hoofdstuk 6

Tijdens het Weichselien zijn in het Nederlandse deel van de Noordzee afzettingen onder allerlei omstandigheden gevormd: fluviatiele, lacustriene, glaciale, fluvioglaciale en periglaciale. De oudste sedimenten bestaan uit stugge kleien en dateren uit het Vroeg-Weichselien en zijn afgezet in de zuidelijke Bocht van de Noordzee in een lacustrien milieu dat ontstond tijdens de verlaging van de zeespiegel. Deze kleiafzettingen worden tot de Brown Bank Formatie gerekend en bereiken dikten tussen 2 m en 5 m. In het centrale en zuidelijke deel van de zuidelijke Bocht zijn door de Rijn en Maas middel- tot grofkorrelige fluviatiele sedimenten afgezet, behorend tot de Formatie van Kreftenheye met dikten tussen <1 en ongeveer 20 m. Ze komen voor in een naar het zuidwesten gerichte delta. Tijdens het Laat-Weichselien drong ijs vanuit Groot-Brittannië de Noordzee binnen en breidde zich tot ver in de Nederlandse sector uit. Het Scandinavische ijs bleef ver ten noorden van het Nederlandse deel. Fijne tot middelkorrelige fluvioglaciale sedimenten van de Well Ground Formatie zijn plaatselijk aangetroffen en zijn afgezet voor de komst van het landijs en tijdens de afsmeltingsfase. Stugge glaciolacustriene kleien van de Dogger Bank Formatie en de Volans Member van deze formatie komen over een uitgestrekt gebied voor. De dikte varieert tussen 4 m en 20 m. In het noordelijk deel langs de grens met het Duitse deel van de Noordzee is een mariene facies van de Dogger Bank Formatie aangetroffen. Keileem van de Bolders Bank Formatie komt voor in het zuidelijk deel van het met ijs bedekte gebied. In het noordelijke deel komt keileem alleen plaatselijk voor. De overgang van de Bolders Bank Formatie in de Dogger Bank Formatie is geleidelijk. Gebaseerd op micro-structuren in de keilemen zijn aanwijzingen gevonden voor zowel het voorkomen van door uitvloeiing afgezette keileem als basale grondmorene.
Plaatselijk zijn grindafzettingen behorend tot de Indefatigable Grounds Formatie aangetroffen, waarvan is vastgesteld dat zij Groot-Brittannië als gebied van herkomst hebben. Er zijn twee typen subglaciale dalen onderscheiden: een vlechtend systeem met opgevulde of gedeeltelijk open dalen, waarvan de basis tot maximaal 80 m beneden MSL ligt. Deze dalen zijn deels opgevuld met zachte kleien en zeer fijne zanden van de Botney Cut Formatie. Het tweede type wordt gevormd door V-vormige dalen in het uiterste noorden van het Nederlandse deel, die zijn opgevuld met de Volans Member van de Dogger Bank Formatie. Gebaseerd op de lengterichtingen van de assen van de subglaciale dalen zijn twee uitvloeiingsrichtingen van het ijs vastgesteld, een van west naar oost tot zuidoostelijke richting en een van noord-noordwest naar zuid-zuidoostelijke richting. In het Nederlandse deel is slechts één tongbekken aangetroffen. Dit bekken ligt binnen de verbreiding van de Dogger Bank Formatie en wijst op ijsbedekking zonder afzetting keileem. Deformatiestrukturen tengevolge van ijsdruk zijn zeldzaam, maar zijn aangetroffen langs het tongbekken en nabij de Botney Cut. Zeer fijne tot fijne periglaciale zanden van de Twente Formatie komen wijdverbreid voor in de oostelijke helft van de Nederlandse sector en bereiken dikten tusssen <1 m en ongeveer 12 m. De afzettingen dateringen uit respectievelijk het Vroeg-, Midden- en Laat-Weichselien. Plaatselijk zijn interstadiale veenlaagjes aangetroffen. ^{14}C-dateringen geven ouderdommen aan van 45.090 +3750/-2500 BP, 11.280 ±40 BP en 10.945 ±50 BP. De sedimenten van de Doggersbank en haar vermoedelijke wijze van ontstaan en aanwijzingen voor drainage tijdens het Weichselien worden besproken.

Hoofdstuk 7

Het dynamisch gedrag en de uitbreidingen van de ijskappen van de drie laatste glaciaties in de Noordzee, de verschillen in erosieve en sedimentaire processen worden vergeleken en besproken. De drie ijskappen blijken verschillende fysische karakteristieken te hebben gehad. De Scandinavische ijskap van het Elsterien strekte zich tot ver in de Bocht van de zuidelijke Noordzee uit en bereikte de Britse oostkust. De produktie van smeltwater moet enorm groot zijn geweest gezien de diepe dalen die onder het ijs zijn geërodeerd. De Scandinavische ijskap van het Saalien strekte zich alleen uit in het oostelijk deel van de Nederlandse sector. Er is geen bewijs gevonden voor de aanwezigheid van Brits ijs in de zuidelijke Noordzee. De produktie van smeltwater moet tijdens het Saalien aanzienlijk minder zijn geweest dan tijdens het Elsterien gezien de veel kleinere subglaciale dalen die zijn gevormd. Tijdens het Laat-Weichselien bereikte de Scandinavische ijskap het Nederlandse deel van de Noordzee niet. Het Britse ijs drong echter door tot in het Nederlandse deel en vormde hier een vlechtend patroon van relatief ondiepe subglaciale dalen.

ABSTRACT

Chapter 1

A recent publication (Cameron, et al., 1993) is used as an introductory basis to this thesis in order to provide an outline of the development of the North Sea Basin from pre-Permian times to the Holocene.

Chapter 2

A brief description of the drilling and coring techniques and methods available is given to indicate the range and value of the samples collected. The seismic systems used and the advantages and problems of these methods of data collection are discussed. The value of macro- and micropalaeontological, mineralogical, geochemical and petrological determinations and analyses is briefly described.

Chapter 3

Glacigenenic or 'cold' marine and fluviatile sediments related to Early Pleistocene glaciations are present at only a few locations in boreholes in the British, Dutch, German Danish and Norwegian sectors. In the Dutch sector the oldest indications of glacial influence probably date from the Tiglian C4c cold Stage. Stiff marine clays of the IJmuiden Ground Formation recorded in at least one, possibly two, boreholes are thought to date from this early glaciation. Indications of sediments deposited during the Eburonian Stage and in a pro-delta and delta front environment are present in a deep borehole and are referred to the Winterton Shoal Formation. Fluviatile sediments deposited by the rivers Elbe and Weser during the Menapian Stage are present in only two boreholes. The oldest glacigenic sediments recorded are present in a borehole near the Dogger Bank and were probably deposited during the Cromerian Glacial A or B. 'Cold' marine sediments of Cromerian age are known to be present in a borehole farther east. Correlation of the 'cold' sediments between boreholes is not possible due to the large distance between localities and also the fact that in most boreholes sediments of only one cold stage are recorded.

Chapter 4

The glacial sediments and features associated with the Middle Pleistocene Elsterian glaciation are more widespread than those of the Early Pleistocene glaciations. During the Late Elsterian glaciation a pattern of wide and deep valleys were eroded by subglacial processes in a zone extending between 53°N and 55°N and running from the Irish Sea into Poland. Most of the Elsterian sediments between the subglacial valleys and the shoulders of these valleys fall in a 'seismic gap' between the maximum penetration of the high resolution 3.5 kHz seismic system, and the resolution of low frequency systems. Due to this lack of seismic data considerable reliance has been placed on the interpretation of boreholes which penetrate to below about 100 m below the sea bed. The deeper part of the infill of the valleys has only been described from seismic interpretations. The upper part of the infill appears to be mainly glaciomarine clay deposits of the Swarte Bank Formation deposition of which probably took place during the retreat of the ice. At the end of the glaciation marine conditions prevailed in the Dutch sector and this marine sedimentation continued during the following Holsteinian Interglacial Stage with probably no hiatus in sedimentation. In contrast with the following two

glaciations Elsterian till of the Juisterriff Formation has only been found to date at one location.
At the southern limit of the Elsterian ice sheet, and near the present Brown Bank, tongue-shaped basins are present along which deformation structures caused by ice-push have been recorded.
Periglacial sediments of the Middelrug Formation, and deposited prior to the glaciation, have been found only locally. They reach thicknesses between about 4 m and 6 m. At the end of the glaciation no periglacial sediments were deposited due to the prevailing marine conditions.

Chapter 5

Many of the sediments and features associated with the Saalian cold stage are much better known than the preceding stage, this largely due to the fact that they mostly fall well within the penetration depth of high resolution 3.5 kHz seismic systems. As a result of this the geometry of the Saalian periglacial, glaciolacustrine and glacigenic deposits have been mapped in more detail.
From the period immediately preceding the Late Saalian glaciation the only sediments present in the Dutch sector are very fine- to fine-grained periglacial sediments of the Tea Kettle Hole Formation. The formation occurs mainly in the northern part of the Dutch sector and ranges in thickness between 1 m and 10 m. In a valley in the eastern part of the sector, however, overlain by Late Saalian till, marine sediments are present probably which may indicate arctic to boreal marine conditions during an Early Saalian Interstadial. The Scandinavian ice sheet entered the southern North Sea during the Late Saalian and extended into part of the Dutch sector. Stiff to very stiff glaciolacustrine clay of the Cleaver Bank Formation was deposited in the north and north-west parts of the Dutch sector generally reaching thicknesses between 4 m and 6 m. Tills of the Borkumriff Formation are present near the northern coast of The Netherlands and based on their lithology two different facies can be distinguished. In the east the till contains up to 47 % of gravel while in the west only up to 3% of gravel has been recorded. The thickness varies between <1 m and 10 m. Fine- to medium-grained fluvioglacial sediments of the Molengat Formation are only found very locally. The extent of the formation was probably greater, but much of it was reworked during the Eemian transgression. The Eemian sediments generally consist of medium- to fine sand and contain Scandinavian gravel. The occurrence and nature of the Saalian subglacial valleys is problematical. The dimensions of the valleys are much smaller than those of the Elsterian glaciation and they are partly filled with Eemian marine sediments. Since, on 3.5 kHz seismic records, the base of some of the valleys occurs below the penetration depth. It is difficult to distinguish Saalian valleys from those formed during the Eemian transgression. Tongue-shaped basins with deformation structures along their flanks are only found at two locations. In the northernmost part of the Dutch sector icings (naledi) have probably been recorded. Glacial gravel occurrences on the sea bed, referred to the Indefatigable Grounds Formation with thicknesses of <1 m, indicate a Scandinavian origin. The absence of so-called Hesemann counts on gravel occurrences in the North Sea, and also the lack of measurements on orientation of the axis of boulders in the till does not enable a reconstruction of the flow directions of the ice sheet to be made. Based on the glacial sediments, and the occurrence of other glacial phenomena, a more detailed reconstruction than was hitherto possible of the maximum extent of the ice sheet in the Dutch sector has been made.
The indications for absence of a British Saalian ice sheet in the southern North Sea are discussed.

Chapter 6

A wide range of fluviatile, lacustrine, glacial, fluvioglacial, glaciolacustrine, and periglacial sediments were formed during the Weichselian glaciation in the Dutch sector of the North Sea. The oldest sediments from the Early Weichselian, stiff clays, were deposited in the southern Bight of the North Sea in a lacustrine environment. The clays are referred to the Brown Bank Formation reaching thicknesses between 2 m and 5 m. In the central and southern parts of the southern Bight of the North Sea medium to coarse-grained fluviatile sediments of the Kreftenheije Formation were deposited by the rivers Rhine and Meuse in the form of a south-west trending delta with a thickness between <1 m and 20 m. During the Late Weichselian an ice sheet from Britain entered the southern North Sea and extended into the Dutch sector. The Scandinavian ice sheet however did not extend as far south as the Dutch sector. Fine- to medium-grained fluvioglacial sand of the Well Ground Formation is recorded locally. The formation was deposited both prior to the advance and during the retreat of the British ice sheet. Glaciolacustrine stiff clays of the Dogger Bank Formation are widespread and range in thickness between 4 m and 20 m. In the north and along the median line between the German and Dutch sectors a glaciomarine facies of the Dogger Bank Formation is present. Tills of the Bolders Bank Formation are present in the southern part of the glaciated area and also locally in the northern part. A gradual transition is present between the Bolders Bank and Dogger Bank formations. Micro-structures indicate deposition of both flow and lodgement tills. Studies on the glacial gravels of both the Indefatigable Grounds and the Bolders Bank formations have identified them as originating from Britain. Two different types of subglacial valleys are present. The first type consists of a braided system of partly open valleys with their bases up to 80 m below MSL and occurring near the southern limit of the ice, and infilled with soft clays and fine-grained sediments of the Botney Cut Formation. The second type consists of V-shaped valleys in the north and infilled with the Volans Member of the Dogger Bank Formation. Based on the occurrence of subglacial valleys two main ice-flow directions of the British ice have been recognised, one from the west and south-west near the southern limit of the British ice and from the north-east in the northern part of the Dutch sector. In the Dutch sector only one tongue-shaped basin has been recorded and is present in the Dogger Bank Formation. This indicates ice cover without accompanying deposition of tills. Deformation structures due to ice-push are rare. Very fine- to fine-grained periglacial sediments of the Twente Formation are widespread, occur mainly in the eastern half of the Dutch sector and were deposited during the Early, Middle and Late Weichselian. Locally interstadial peat has been sampled and dated by the ^{14}C method. Various ages, including 45,090 +3750/-2550 BP, 11,280 ±40 BP and 10,945 ±50 BP have been recorded.
The sediments of the Dogger Bank, the probable genesis of the bank and the possible drainage patterns in the North Sea are also discussed.

Chapter 7

The dynamic behaviour and extent of the ice sheets of the three last glaciations in the North Sea Basin and their differences in terms of both erosional and sedimentary processes are compared and discussed. These ice sheets appear to have had different specific physical characteristics. The Scandinavian Elsterian ice sheet extended far into the southern North Sea and even reached the British east coast. The production of meltwater must have been considerable in view of the enormous amounts of sediment which have been eroded during the formation of deep subglacial valleys. By contrast the Saalian Scandinavian ice sheet extended only as far as the eastern part of the Dutch sector and no evidence for British ice has been

found in the southern North Sea during the Saalian glaciation. The amount of meltwater appears to have been considerably less if the evidence provided by the 'shallow' subglacial valleys compared with their Elsterian counterparts is taken into account. During the Late Weichselian glaciation the Scandinavian ice sheet did not reach as far south as the Dutch sector of the North Sea. The British ice sheet, however, extended east into the northern part of Dutch sector and formed a braided system of shallow subglacial valleys.

I INTRODUCTION

The Geological Survey of The Netherlands (RGD) in co-operation with the Ministry of Public Works began geological investigations in the North Sea during the mid sixties. Although the initial purpose of these investigations was offshore sand and gravel resources, the discovery of Late Pleistocene clay deposits near the sea bed stimulated considerable scientific interest. As a result a North Sea department within the RGD was established in 1968 and a reconnaissance study was started in the Dutch sector of the North Sea - an area almost twice the Dutch land surface. During the late sixties the oil and gas industry began exploration in the Dutch sector and this data, including leg-penetration tests for drilling rigs, became avail- able to the RGD. Especially in the area north of 53°N a large number of well-cored boreholes up to 100 m in depth were drilled for this purpose. Oele (1969; 1971), published the first results including a tentative interpretation of the data collected since 1967. The co-operation between the North Sea Directorate of the Ministry of Public Works and the RGD was formalised in the early seventies, whereupon plans were made for a mapping programme covering the entire sector. The systematic survey and collection of data began using the mv Volans as a survey vessel utilizing the (then) newly developed high resolution seismic systems and various coring devices and sampling gear. Two seismic lines and at least 5 boreholes up to 10 m deep below the sea bed were sunk in each oil and gas licence block while additional vibrocores up to 4.5 m below sea bed were collected at special locations.

In the late seventies the British Geological Survey (BGS) invited the RGD to co-operate in its offshore mapping programme, at a scale of 1:250,000, along the median line dividing the British and Dutch sectors. As result five sheets were completed within a 10 year period. The sheets from south to north respectively include Ostend, Flemish Bight, Indefatigable, Silver Well and Dogger. Each component sheet area consists of three separate maps, notably a Solid map (pre-Quaternary geology), a Quaternary map (Pleistocene geology) and a superficial Sea Bed Sediments and Holocene geology map. The early nineties saw the completion of joint RGD/BGS area and the RGD is now mapping the Oyster Grounds area.
The seismostratigraphy of the Quaternary of the southern North Sea was largely established during the co-operative programme with the BGS. In addition to the regular mapping programmes detailed studies were carried out in co-operation with students from the Universities of Leiden, Amsterdam, Utrecht and the Free University of Amsterdam. Students from the University of Edinburgh, using RGD data, studied the Early Pleistocene development of the southern North Sea Basin prior to the Elsterian glaciation, and the genesis and infill of the Elsterian glacial valleys. Students from the University of Århus in Denmark studied three glacial valley systems in the Danish sector of the North Sea using seismic data collected during the EC Southern North Sea Project.

A large number of papers dealing with the Quaternary history of the British sector of the North Sea have been published. Due to lack of available data comparatively little is yet known regarding the geological history of both Danish and German sectors of the North Sea.

II OBJECTIVES

In the Dutch sector of the North Sea a wide range of sediments and bedforms related to glacial and periglacial conditions are present.
The objective of this thesis is:

- To describe the characteristics, lithology, genesis, morphology and, where relevant, the palaeontology of the glacial sediments of the Dutch sector of the North Sea.
- To reconstruct the sedimentary and environmental conditions during deposition of the sediments.
- To establish the geometry of the lithostratigraphic units.
- To describe and discuss the influence of the Pleistocene glaciations on the development of the Dutch sector of the southern North Sea Basin and the related sediments and bedforms.
- Where relevant existing information on the glacial stages prior to the Elsterian glaciation is described and correlated with data from land areas on both sides of the North Sea.
- To compare the sediments and bedforms of the three last glaciations based on both their sedimentary record and glacial characteristics.
- To discuss the maximum extent of the ice sheets in the Dutch sector of the North Sea in the light of present evidence.

Chapter 1

Geology of the southern North Sea Basin

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Abstract
The southern North Sea Basin has had a long and complex geological history. Between the Late Carboniferous and the end of Triassic times, the basin was largely confined between two ancient east-west trending Palaeozoic upland areas: the London-Brabant Massif and the Mid North Sea High/Ringkøbing-Fyn High. Crustal stretching, followed by thermal subsidence, then enabled up to 3500 metres of Jurassic, Cretaceous, Tertiary and Quaternary sediments to accumulate, with the depocentre striking NNW from The Netherlands towards the central North Sea. Late Miocene, Pliocene and Early Pleistocene sedimentation was dominated by the build-out of major delta systems across the basin, principally from its eastern seaboard. The subsequent history of the basin has included three episodes of regional glaciation, punctuated by strongly tidal, marine environments similar to those of the present day.

Introduction
Since the search for hydrocarbons beneath the southern North Sea began in the 1960s, more than 2000 wells have been drilled to a maximum depth of 5000 m, and more than a million kilometres of digitally recorded seismic-reflection data have been acquired by the oil exploration companies. Much geological information has been published in many hundreds of papers, and the structural setting and stratigraphy of the Late Carboniferous to Tertiary sediments have been particularly well established in the area north of 52° 30' N in which the hydrocarbons occur.

Pre-Permian basin development
Basinal marine and volcaniclastic Lower Palaeozoic sediments, mildly metamorphosed during the Caledonian orogeny, form the basement to much of the southern North Sea; crystalline Pre-Cambrian rocks are probably also present at depth beneath the London-Brabant Massif. Except over the crest of the London-Brabant Massif, where they approach to less than 1 km belowthe sea bed, the Lower Palaeozoic rocks and their patchy cover of mainly alluvial Devonian sediments are now buried beneath many kilometres of younger Palaeozoic, Mesozoic and Cenozoic sediments. The thickest Devonian deposits occur towards the east of the Mid North Sea High, where they contain evidence for temporary Middle Devonian northward ingression of an embayment of the Proto-Tethys Ocean along a lineament adopted later by the Central Graben of the North Sea (Ziegler, 1990).

The London-Brabant Massif and Mid North Sea High/Ringkøbing-Fyn High (Fig. 1) became established as stable upland areas early in Carboniferous times. Up to 4000 m of deep-water and deltaic sediments were deposited in rapidly subsiding grabens and half-grabens during an Early Carboniferous phase of crustal extension (Leeder, 1987), whereas contemporary horsts accumulated condensed sequences including platform carbonates. As crustal extension diminished, relatively uniform deltaic sedimentary facies spread across central areas of the southern North Sea by Late Namurian times, and up to 3000 m of combined Namurian and Westphalian sediments have been proved by drilling. Although Dinantian and Namurian organic shales and minor coal seams are present, the Lower Westphalian coal measures have been the principal source rocks for many gas fields of the southern North Sea. These were deposited on a low-lying, paralic delta plain (Guion & Fielding, 1988). Later in the Westphalian, regional uplift caused the poorly-drained deltaic facies to be superseded by better-drained, alluvial-plain sedimentation.

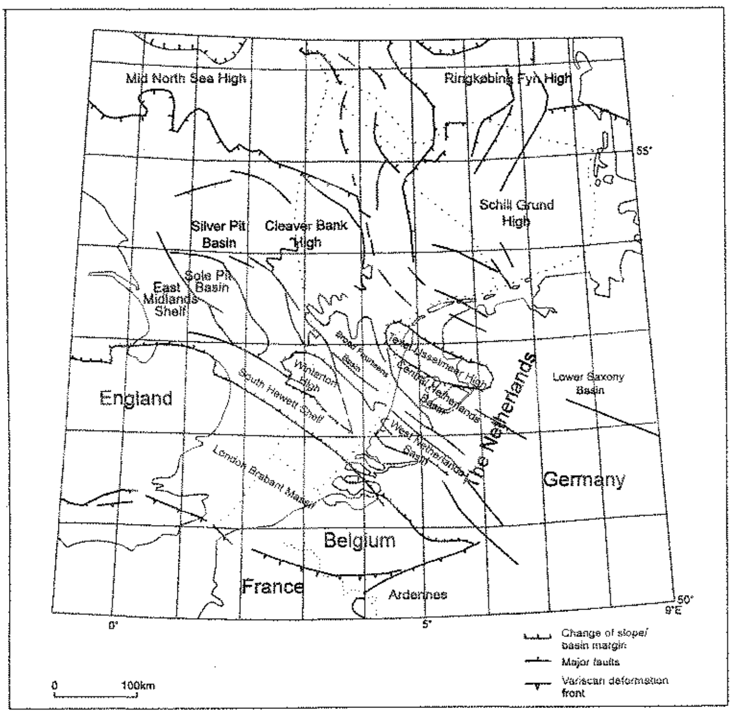

Fig. 1. Regional structure of the southern North Sea Basin.

Early in Westphalian times, the southern North Sea had become a foreland area to a chain of Variscan mountains that extended from south-west England through France into eastern Europe (Glennie, 1990a). Its Carboniferous rocks were gently folded, faulted and peneplaned, and up to 1500 m of sediments were eroded from parts of the current offshore area (Cameron et al., 1992).

Permo-Triassic basin development

Early in the Permian, much of the southern North Sea began to subside gently once more, as the area north of the London-Brabant Massif now lay within an east-west trending Variscan foreland, post-orogenic collapse basin (Ziegler, 1990). This basin which extended between eastern England and Poland until Late Triassic times (Glennie, 1990a), was bounded to the north by the Mid North Sea High and Ringkøbing-Fyn High. These highs accumulated condensed sequences of Permian and Triassic sediments, whereas the London-Brabant Massif continued as a stable upland area. Basal Permian volcanics have been recorded in the Horn Graben of the German and Danish sectors, at the Ringkøbing-Fyn High, and locally elsewhere (Glennie, 1990b).

During much of the Permian, the southern North Sea Basin lay in a rain shadow north of the Variscan mountains (Glennie, 1990b). Lower Permian sediments, including aeolian and fluvial sands, are generally less than 400 m thick and were depositedin an arid desert environment. The aeolian sands occur for up to 150 km north of the London-Brabant Massif, and provide the principal reservoir for the many gas fields in the current offshore area. Contemporary sabkha deposits accumulated around the margins of a desert lake that extended from just off the Yorkshire coast as far east as Germany. The lacustrine sediments include silty mudstones and evaporites, and these are up to 1500 m thick beneath the German Bight of the North Sea.

Five short-lived but widespread transgressions of the Boreal Ocean entered the basin by a temporary seaway late in the Permian (Taylor, 1990); two further transgressions have been recorded in the east of the basin (Best, 1989). Marine shales and carbonates were deposited following the first, second and third transgressions, while evaporites accumulated during periods when constriction of the seaway led to increased salinity in the basin. These evaporites include local salt-pan deposits of the first cycle and basin wide halites, polyhalites and subsidiary salts of the second, third and fourth cycles. The evaporites of the second cycle are especially thick, and have been deforming intermittently by halokinesis since mid-Triassic times, and especially during regional episodes of rifting and basin inversion. Triassic rifting across the Central Graben initiated the salt diapirs illustrated in Figure 2 (section B-B').

Triassic sediments of the southern North Sea are locally several thousand metres thick. Although dominated by reddish-brown mudstones, there are sandstones forming important gas reservoirs in the Lower Triassic, and beds of dolomite, anhydrite, sandstone and widespread halite horizons in the Middle and Upper Triassic. Early Triassic sediments were deposited in playa-lake, floodplain and other fluvial environments (Fisher & Mudge, 1990) at a time of major rifting of the Horn Graben and Central Graben of the North Sea (Ziegler, 1990). Later Triassic sediments also include coastal sabkha deposits and evaporites that record four basin-wide incursions of marine influences associated with transgressions of the Tethys Ocean into east European parts of the basin. A more permanent connection with the Tethys Ocean caused fully marine conditions to spread across the southern North Sea during Rhaetic, Late Triassic times. These marine conditions have continued intermittently during the past 200 million years.

Jurassic to mid-Miocene basin development

It was during Late Triassic and Early Jurassic crustal extension beneath its central axis that the North Sea first adopted its present NNW-SSE alignment. Early Jurassic extension led to particularly rapid subsidence of the Central Graben and the Sole Pit Basin. Predominantly argillaceous marine Lower Jurassic sediments are up to 2000 m thick in the former area, where they include the organic-rich, gas- and oil-prone, Posidonia Shale.
Subsidence was temporarily interrupted by Middle Jurassic domal uplift and deep erosion along the central axis of the North Sea; perhaps as much as 2000 m of sediments were eroded from the Cleaver Bank High at this time (Glennie, 1990a) and from the Schill Grund High. Middle Jurassic sediments, best preserved from later erosion in the western UK sector and in the contemporary rift zone of the Central Graben, include a variety of shallow marine, brackish water, and fluviodeltaic sediments.

Renewed Late Middle Jurassic to Early Cretaceous extension of the crust, beneath the Central Graben by about 18 km (Clark-Lowes et al., 1987) and associated strike-slip movements

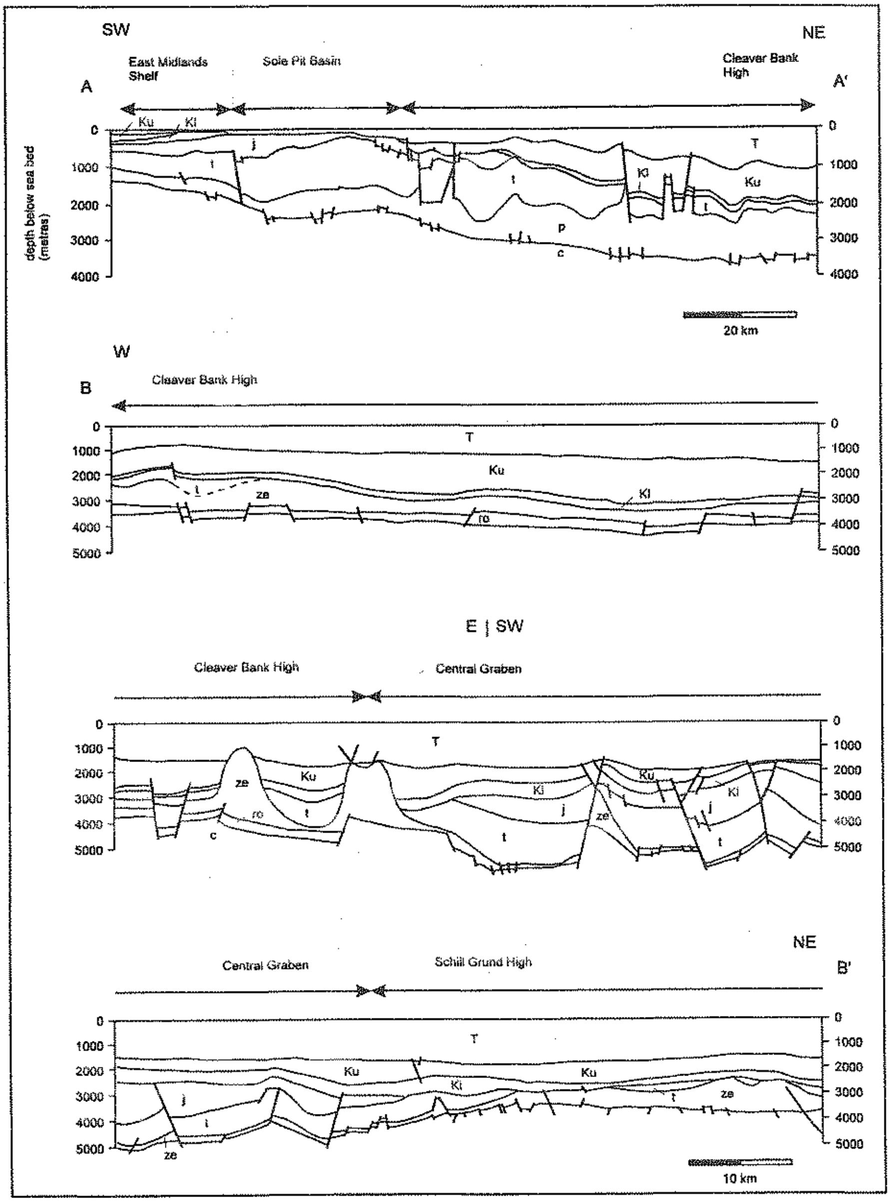

Fig. 2. Schematic profiles across the central UK and Dutch sectors.
T - Tertiary + Quaternary, ku - Upper Cretaceous, kl - Lower Cretaceous, j - Jurassic, t - Triassic, ze - Zechstein, ro - Rotliegend, p - Zechstein + Rotliegend, c - Carboniferous.

along the faults bounding the Broad Fourteens Basin (Glennie, 1990a), then enabled up to 2000 m of Upper Jurassic and Lower Cretaceous sediments to accumulate in these basins (Herngreen & Wong, 1987). Local sediment thicknesses and facies were strongly influenced by the contemporary halokinesis of the deeply buried Upper Permian evaporites. The Upper Jurassic sediments are mainly of shallow marine, paralic and continental facies in the

southern Dutch sector; they comprise paralic overlain by marine argillaceous sediments in the Central Graben, and consist of relatively thin organic-rich, marine shales and minor limestones in the UK sector (Brown, 1990). The Lower Cretaceous sediments are marine, calcareous mudstones and minor sandstones.

Crustal extension ended in mid-Cretaceous times, but the regional thermal anomaly that it generated has been decaying ever since, and this has been the principal mechanism by which the southern North Sea Basin has continued to subside. The influence of fault-bounded basins as the principal depocentres diminished as the whole of the southern North Sea, including the London-Brabant Massif, Mid North Sea High and Ringkøbing-Fyn High, subsided in response to regional downwarping. At various intervals, notably towards the beginning and at the end of the Cretaceous, the fault-bounded basins and adjacent areas were locally subjected to significant uplift and partial erosion of their previously deposited sediments (basin inversion).

A uniform blanket of white, coccolith-rich chalk accumulated in warm, oxygenated waters during Late Cretaceous times, and is up to 1500 m thick. This chalk deposition was interrupted around contemporary basin-inversion structures by local episodes of uplift and erosion. An unconformity separates the Chalk Group from overlying Palaeogene sediments across much of the southern North Sea (Fig. 2), and this records widespread temporary emergence of the area above sea-level around the Cretaceous/Palaeocene boundary. Following submergence and renewed subsidence, up to 1000 m of mainly argillaceous, marine Palaeogene sediments were deposited. Their depocentre lay approximately above the Central Graben and its southward continuation into The Netherlands, whereas the London-Brabant Massif and Ringkøbing-Fyn High accumulated condensed Palaeogene sections.

Mid-Miocene to mid-Pleistocene basin development

Tectonic uplift caused most of the southern North Sea to emerge above sea-level once more during mid-Miocene times in response to regional stresses generated by continental convergence of the Alpine orogeny (Glennie, 1990a). Relaxation of this stress system then enabled subsidence to resume, and between the Late Miocene (about 10 million years ago) and Late mid-Pleistocene times (0.4 Ma) the southern North Sea Basin became the site of one of the world's major delta systems. The associated fluvio-deltaic plain eventually covered an area of at least 150,000 km^2, and the delta-related sediments are between 500 m and 1500 m thick along the central axis of the North Sea.

Delta systems built out at first from the eastern seaboard of the North Sea, fed by former Baltic rivers that drained from the Fennoscandian Shield (Bijlsma, 1981) and by westward-flowing north German rivers that drained from central Europe (Lüttig, 1974; Lüttig & Meyer, 1974; Gibbard, 1988). Build-out of marginal deltas associated with the Rhine, Meuse, Scheldt, and relatively minor British rivers then occurred from the Early Pleistocene, about 1.8 Ma (Zagwijn, 1979), and helped to deflect the principal direction of delta growth from west- or south-westward to north-westward. These rivers were discharging into the southern embayment of an epicontinental sea as there was little if any connection of the North Sea through the English Channel into the Atlantic Ocean from Miocene until comparatively recent times (Cameron et al., 1992).

Miocene deltaic deposits, largely confined to the German and Danish sectors, were deposited as water depth in the east of the North Sea Basin increased rapidly by between 300 m and

500 m (Gramann & Kockel, 1988), an amount that can only have been caused by tectonic subsidence of the German Bight and Ringkøbing-Fyn High, as it was far in excess of contemporary sea-level fluctuation (Haq et al., 1988). Pliocene deltaic deposits are thickest in the central Dutch sector, and were deposited as maximum water depth in the basin decreased to less than 150 m (Cameron et al., 1993). Deltaic deposits in the UK sector are largely Pleistocene in age, and their deposition resulted in complete filling in of the southern North Sea Basin, and expansion of its fluvio-deltaic plain to at least as far as 56° N by mid-Pleistocene times.

Regional seismic interpretation, calibrated by the results of boreholes, has shown that the deltaic deposits comprise an upward-coarsening megasequence at any location in the southern North Sea (Cameron et al., 1987). Argillaceous, often intensely bioturbated prodelta sediments are overlain successively by muddy delta-front sands and clays, by delta-top facies including shallow subtidal, intertidal and non-marine sands and clays and by clean, locally gravelly, fine- and medium-grained fluvial sands. These facies record the approach and overwhelming of that location by the advancing deltas. The fluvial sediments are thickest in the east of the basin, where they have the greatest, Pliocene to mid-Pleistocene age range.

The regional seismic interpretation has also revealed that deltaic sedimentation was punctuated many times by intervals of regional stratigraphic hiatus or of basin-wide change in sedimentary environment. Such intervals generate sequence boundaries on the seismic profiles, and they may be the product of fluctuation in relative sea-level within the basin, change in subsidence rates, or of sediment supply to the basin. Whatever their cause, they suggest that progressive infill of the southern North Sea Basin was accompanied by cyclic fluctuation of its coastlines, perhaps by many tens of kilometres, in response to one or more of these factors.

Mid-Pleistocene to Holocene basin development

There is abundant evidence from the palaeobotanical record of The Netherlands for cyclic fluctuation between warm temperate (interglacial) and cold climatic conditions in the North Sea Basin and its hinterland from Early Pleistocene times (Zagwijn, 1989a). Climatic severity notably increased during the cold (glacial) climatic stages of the Middle Pleistocene, leading to glaciation in the basin's peripheral sediment source areas (Boulton, 1992), but it was not until the Elsterian Stage that began about 0.4 Ma ago that there was the first of three widespread invasions of ice across the basin itself. Following each of these glaciations, climatic amelioration led to the development of strongly tidal, marine environments similar to those of the present day.

Elsterian ice cover was accompanied by erosion of a swarm of anastomosing, but mainly north-south or north-north-west trending glacial palaeovalleys cut into the Pleistocene and pre-Pleistocene strata (Long et al., 1988). The largest valleys, up to 23 km wide and >450 m deep, are boat-shaped in longitudinal section with an uneven thalweg. In the southern North Sea, they are mainly concentrated between 53° and 54°N, but contemporary valleys are also widespread beneath the northern Netherlands and north Germany.
The mechanism by which such valleys were formed is still a matter of controversy, but most authors favour a subglacial meltwater (Boulton & Hindmarsh, 1987) or jökulhlaup origin (Wingfield, 1990). The valleys were partially filled by diamictons, outwash gravels and sands, thick lacustrine clays, and fluvial sands before the climatic amelioration of the Holsteinian Stage.

If there were contemporary glacial or periglacial deposits south of 53°N, then they have been completely removed by subsequent erosion.

Early in the Holsteinian Interglacial Stage, rising sea-level led to the re-establishment of a shallow sea, the shorelines of which lay partly landward of those of the present North Sea (Cameron et al., 1992). The glacial palaeovalleys which had not already been filled by Elsterian deposits contain an additional component of marine Holsteinian sediments, typically clays or fine sands. These accumulated in a quiet, shallow-water environment, but open-marine conditions were eventually established during deposition of up to 25 m of sparsely shelly sands in the Dutch sector (Laban et al., 1984). Farther south, Holsteinian sediments were deposited along the Franco-Belgian border during transgression from the south-west (Sommé, 1979); Paepe & Baeteman, 1979). There was probably no marine connection between the North Sea and the English Channel through the Dover Strait at this time (Zagwijn, 1979; Hinsch, 1985).

Following climatic deterioration and marine regression, thick ice sheets spread across Denmark, northern Germany, and the northern Netherlands during the Saalian glaciation, but the ice cover extended no more than 100 km north-west of the present Danish and Dutch coastlines (Foged, 1987; Joon et al., 1990). Spreads of till continue offshore, and ice-pushed ridges and subglacial valleys formed within the limits of the ice sheet. Proglacial lacustrine clays, outwash sands, and wind-blown sands were deposited in a periglacial environment beyond the ice margin.

Following deglaciation, rising sea-level led to the establishment of a shallow sea once more during the Eemian Stage. At the sea's maximum extent, when north European winter temperatures were significantly warmer than those of today (Gerasimov & Velichko, 1982), its shorelines extended partly beyond those of the present North Sea. Eemian marine sands locally have a much higher shell content than those deposited by the Holsteinian or Holocene transgressions (Cameron et al., 1989), and the molluscan fauna has a strong Lusitanian affinity (Spaink, 1958).

Regional climate began to deteriorate late in the Eemian Stage and early in the succeeding Weichselian Stage. When sea-level had fallen by about 40 m, a brackish-water lagoon occupied much of the southern Bight of the North Sea, between East Anglia and The Netherlands (Cameron et al., 1989). This became a freshwater lagoon as sea-level continued to fall; there is no record of the sedimentary environment during the early stages of climatic deterioration elsewhere in the North Sea.

Regional climate continued to deteriorate until, at the height of the Late Weichselian glaciation, sea-level fell to at least 110 m below that of the present day (Jansen et al., 1979a). In the west, a lobe of grounded ice extended from the English coast into the central Dutch sector of the North Sea.
This ice sheet deposited a blanket of pebbly clay-rich till that merges north-eastwards with a proglacial, water-laid diamicton and glaciolacustrine clays (Cameron et al., 1992). A system of glacial palaeovalleys was eroded during ice decay; their orientations are approximately normal to the inferred ice margin, and their dimensions are notably smaller than those of the Elsterian glaciation, implying thinner ice cover (Jeffery, op cit.). A second lobe of grounded Scandinavian ice extended into the North Sea from the coast of Jutland, Denmark. Its limits

are poorly defined offshore but there was no connection across the North Sea between the UK and Scandinavian ice sheets at this time (Cameron et al., 1987; Long et al., 1988).

Aeolian and fluvioglacial sands were deposited over large areas of the North Sea beyond the Late Weichselian ice margin.
Cryoturbation and frost-wedge structures indicate that periglacial conditions prevailed across these newly emergent areas. The Elbe river system, with its tributaries the Weser and Eider rivers, flowed north-westwards from the German coast across the present sea floor in a 30-40 km wide valley system (Figge, 1980), and the Rhine and Meuse rivers deposited extensive, and locally gravelly sands offshore of their modern estuaries (Cameron et al., 1989).

As the Late Weichselian ice sheet began to decay, rising sealevel enabled glaciomarine muds to be deposited in relict palaeovalleys and in present deep water, north-western areas of the southern North Sea. The earliest brackish water incursion into remaining deep water areas may have occurred as early as 10 ka BP (Eisma et al., 1981), when sea-level was about 65 m below present (Jelgersma, 1979). With continuing sea-level rise, tidal sand ridges formed west of the Dogger Bank, which became isolated by tidal erosion of the east-west trending Outer Silver Pit to form a temporary island. Tidal flat sedimentation became more widespread between 9 ka and 8 ka BP. The southern North Sea was connected with the English Channel through the Dover Strait about 8.3 ka BP, and fully marine conditions became established widely after 7 ka BP (Eisma et al., 1981). Deposits of the Early Holocene transgression indicate a unidirectional landward migration of the shoreline during this period. These deposits are thicker than 10 m only in the tidal sand ridges, in the Elbe palaeovalley, and in the south-eastern German Bight.

Detailed records of more recent sea-level change are complicated by the effects of isostatic uplift following the last glaciation, and of continuing tectonic subsidence along the central axis of the North Sea. Such records are largely determined by radiocarbon dating of peat layers that lie directly beneath transgressive marine beds at the Dogger Bank and at various sites between there and the modern coastline. Streif (1985; 1990a) has deduced the history of sea-level change in the German Bight from a study of the complex, interdigitating succession of channel, tidal flat and brackish-water deposits, intercalated peat layers and beach sands that occurs along the north German coastline. These deposits are up to 35 m thick, completely masking the relief of the underlying Pleistocene land-surface.
Tidal-flat sedimentation extended to the Frisian Islands at 7.5 ka BP when sea-level was 25 m below present (Streif, 1985; 1990a). The shoreline has migrated landwards by between 10 and 20 km since then, but sedimentary facies indicate that there were periods of reduced sea-level rise between 4.8 and 4.2 ka BP and between 3.3 and 2.3 ka BP. The sea-level lowered temporarily at about 2.7 ka BP and 2.0 ka BP.

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The references in this paper are included in the main reference list at the end of the publication.

Chapter 2

Methods

2.1 Data collection

The investigation of the sea bed is highly dependent on the development of geophysical and sampling technology. Since the late sixties most of the geological information at sea has been obtained by acoustic methods. A wide range of systems has enabled geologists to acquire continuous vertical seismic profiles to depths varying from a few metres to kilometres.
In co-operation with Bureau Havenmonden (1968-70) and the North Sea Directorate of the Ministry of Public Works (1970 to present), a network of high resolution seismic lines have been run in the Dutch sector of the North Sea. From 1969 until 1978 the Sonia 3.5 kHz seismic pinger system was used while from 1978 up to the present day ORE-pingers and a multichannel system are utilized to carry out this work. In each hydrocarbon licence block at least two diagonal lines have been run while in geologically complex areas these are supplemented by additional lines often using both systems. In addition to seismic surveys a dense pattern of cored boreholes has been drilled.

2.2 Reflection seismics

2.2.1 Principles

This seismic technique is used in frequencies ranging from about 100 to 10,000 Hz. The seismic source (as for instance a pinger transducer, boomer, sparker, watergun, sleevegun or airgun) is either mounted on the hull, or towed behind a ship within or without a 'fish'. The elastic waves produced by the source are partly reflected by the sea bed and partly by other acoustic impedance contrasts below the sea bed. The reflections are received by a transducer or a hydrophone array which is towed behind the ship, and which is close to the seismic source. From the hydrophone the reflected signals are sent to processing and recording equipment on board the ship (Fig. 3).

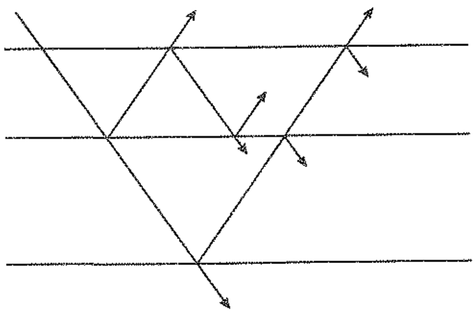


Fig. 3. Reflection and transmission model showing the path of the signal. The horizontal lines represent different lithologic units. At each change in acoustic impedance part of the energy will be transmitted and reflected (after 't Hart, 1979)

2.2.2 Registration

The time registered between the outgoing and incoming reflected signals is used to calculate the depth to the top of the reflecting layers. The ship's speed will depend on the system being used but may vary from 4.5 to about 7 knots (1 knot= 1 nautical mile= 1852 m/per hour). A recorder continually registers the reflected signals on special graph paper.

Three main factors are of importance in obtaining satisfactory results from a geophysical survey. These are respectively depth of penetration of the signal, the propagation velocity of the various rock types encountered, and the resolution. These factors are briefly discussed below.

2.2.3 Penetration

During the travelling of the signal through different sediments, absorption and geometric spreading cause loss of energy. The maximum depth of penetration is thus limited.

Penetration depends mainly on the following factors:
- The acoustic power i.e. the strength of the signal.
- Absorption by conversion of the acoustic energy into heat.
- Scattering. Gravel, boulders and gas-charged sediments cause a dispersion of the acoustic energy in all directions. The remaining energy is often too small to reflect information from deeper sediments.
- The detection limit of the hydrophone or transducer.
- Environmental noise e.g. ships thruster and engines.
- The loss of energy in the water column by geometric spreading.
- The impedance contrast.

2.2.4 Propagation velocity

The propagation velocity of sound in sediments is determined by the properties of the sediment particles. Grain size, porosity and density are the most important parameters (Fig. 4a, b, c and Fig. 5).

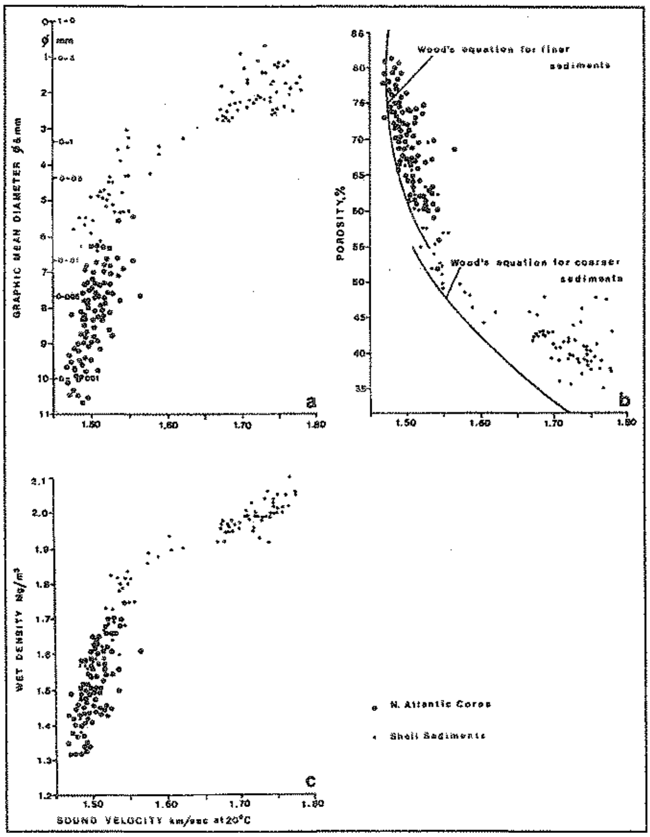


Fig. 4.
a. The relationship between sound velocity and mean diameter of the grains. In general the sound velocity increases with grain size.
b. The relationship between porosity and sound velocity. The sound velocity decreases with increase of porosity.
c. The relationship between density and sound velocity. The sound velocity increases with density ('t Hart, 1979).

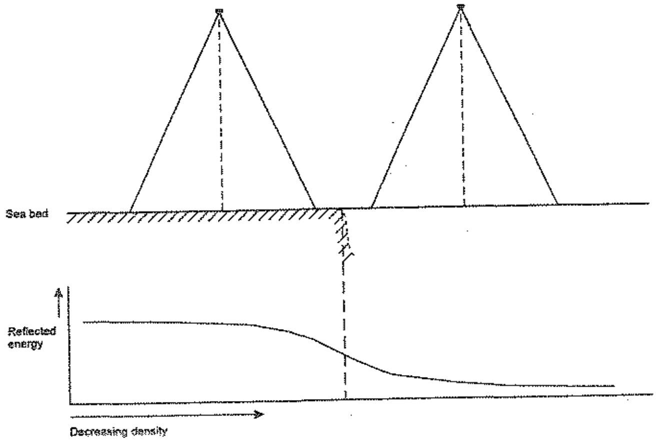


Fig. 5. The reflected energy depends highly on the density of the sea bed (after 't Hart, 1979).

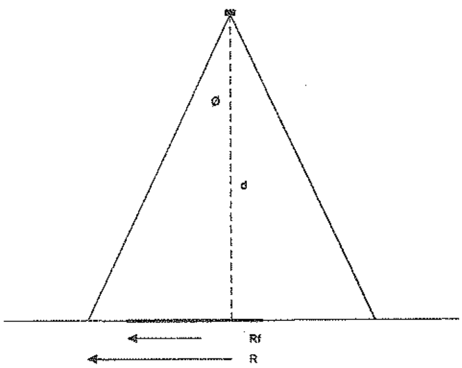


Fig. 6. The resolution is mainly determined by the top angle ø of the transducer, the pulse length and the frequency of the signal (d= distance between transducer and sea bed, 2ø= the top angle, Rf=1st fresnel zone). Rf determines the reflected energy where R is the radius. The smaller the reflection area the better the resolution (after 't Hart, 1979).

2.2.5 Resolution

Resolution is determined by the top-angle of the directional characteristic of the transducer and the band width of the reflected signal. The vertical resolution (width of the first fresnel zone) depends on the top-angle of the transducer, the dominant wavelength, pulse length and band width of the signal (Fig. 6). Loss of energy increases with the frequency from low to high values i.e. the higher the frequency the greater the loss of energy. As a result low frequency waves have a greater penetration depth. However, the resolution shows the same correlation that is, the higher the frequency the greater the resolution or the lower the frequency the poorer the resolution. In effect this means that the greater penetration depth of the low frequency waves is accompanied by a decrease in vertical resolution.
The horizontal resolution is determined by the effective reflecting surface.

2.2.6 Sound velocities and real time conversion

The registration on the seismic profile reflects the two-way travel time of the acoustic signal. The depth to a reflector equals = $\frac{\text{time x velocity}}{2}$

To convert travel times to metres, necessary data about sound velocities in the different sediment layers is required and this information can be obtained from boreholes. Reflectors as shown on the geophysical profiles are compared with the lithology encountered in the borehole. From this the sound velocities in the different layers can be calculated. Depending on

the grain size, porosity and density of the sediments in the southern North Sea, velocities can range from 1500 m/s in water to >1800 m in sand with clay. The sound velocity used for the interpretation of the seismic profiles for the present study was 1800 m/s. Using P-wave measurement equipment the sound velocity can be measured very accurately on undisturbed cores.
The increase in sound velocity in the transition from sand to clay does not cause a strong reflection. By contrast however, the decrease of sound velocity from clay to sand often causes a strong reflection (Fig. 7).

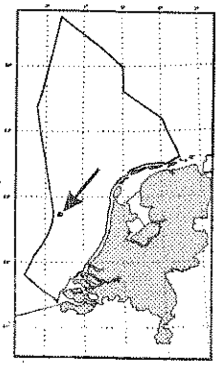
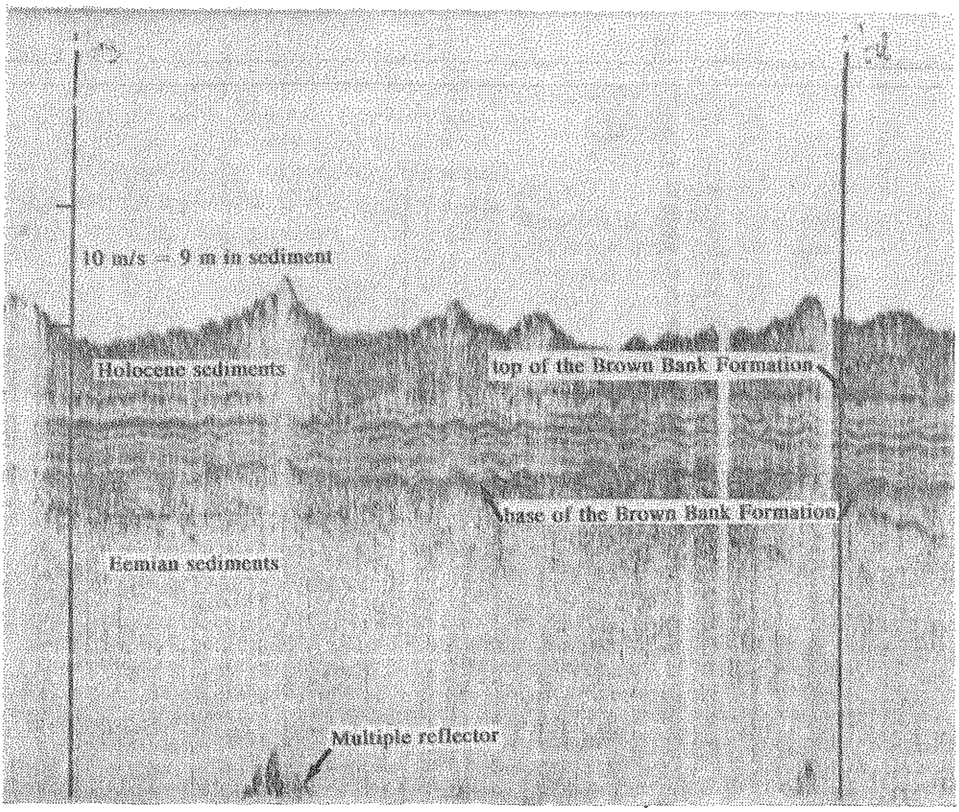


Fig. 7. High resolution seismic profile 3.5 kHz (Sonia) showing the acoustic laminated clay of the Brown Bank Formation in the P blocks. The reflector between the transition from sand to the underlying clay is locally weak due to the increase of wave velocity. The transition from clay to the underlying sand causes a relatively strong reflector due to the decrease of wave velocity.



Photograph J.M.P.K. van Delft

2.3 High frequency seismic systems

Most of the high frequency seismic profiles examined in this study were obtained with the use of Sonia seismic equipment (pinger) owned and developed by Cesco (Van Overeem, 1969). This system, (now no longer operational), consisted of a large transducer with 150 ceramic elements and an acoustic power of 7 kW. The following frequencies were used: 1.5 to 3.5 and 6 kHz, the 3.5 kHz frequency producing the best results. The vertical resolution depended on the pulse length, which was 1/3 m/s with 3.5 kHz. However in practice the resolution appeared to be about 1 metre.
Additional lines, especially in the coastal area, were surveyed using an ORE-180 4 transducer pinger system built in a polyester 'fish' incorporating a wave compensator. This compensator allows seismic surveying to be carried out under less favourable weather conditions.

2.4 High resolution low frequency systems

In order to collect seismic information from deeper layers various types of single and multichannel seismic equipment have been used. The advantage of these lower frequency systems is that information from below the first sea bed multiple can be recorded. Despite this however, the seismic interpreter is nevertheless faced with the difficulty of unscrambling and deciphering multiples which interrupt or obscure the primary reflections on the profiles. Below the first sea bed multiple, multiples of reflectors in the zone between the sea bed and the first multiple are also recorded. This can complicate the interpretation of the profile.
Another disadvantage is that of the vertical resolution. The pulse length of the low frequency systems is long, for instance up to 7 metres or more. Within these distances no reflectors can be distinguished.
The single channel systems used by RGD from 1979 to the mid-eighties were three- and nine-element EG&G sparkers with frequencies varying between 500 and 2000 Hz and an electrical power of 300 J to 1 kJ and 300 J to 4.7 kJ respectively. The receiver used was a Benthos 200-element streamer.

Despite difficulties in the use of multichannel systems nevertheless it offers great advantages since such systems allow the removal of multiples by processing.
The sources used during multi-channel seismic surveys include Sodera S80 waterguns (15 in^3 or 80 in^3) and a Texas Instruments 10 in^3 sleevegun. The shot interval is 5.5 s. but this to some extent, depends on the ships speed. The hydrophone array is a 12 channel Prakla Seismos ministreamer. The seismic data are bandpass filtered (32 - 640 Hz) and recorded by an HR 6300 Geomécanique system with a sample rate of 0.5 ms and a record length of 1.6 s.

2.4.1 Processing

The processing is carried out at RGD using a microVax (SKS) or a Sun (Promax). The main steps in a standard processing sequence (see Arthur, 1980 for details) are as follows:

- **Making-up Common Depth Point (CDP).**
  The data traces which have similar points of reflection are grouped together.
- **Spherical divergence correction.**
  The energy spreads spherically from the source and will decrease with the distance from the source. Because the energy density is inversely proportional to the square distance travelled it can be corrected in a simple way.

- **Velocity analysis.**
  At different points velocity/time curves are constructed.
- Normal move-out correction and mute.
  Using velocity distributions a time correction is applied to the reflection arrival times in order to eliminate the variation caused by differences in source-receiver distance.
- **Stacking.**
  The traces grouped together in the CDP gather are added to give one output trace. For the 12-group streamer, used by RGD, an increase of the signal to random noise ratio by a factor of $\sqrt{12}$ and attenuation of multiples in favour of primaries by a factor of 12 can be achieved.
- **Deconvolution.**
  This operation has been designed to attenuate multiples.
- **Equalisation.**
  This compensates for the loss of energy by absorption through the sea bed. The gain of different channels is adjusted so that the amplitudes are comparable.

2.5 Interpretation problems

The advantage of using high resolution systems lies in the fact that the shape and extent of certain geological phenomena can be recorded in a very accurate way. The character of the reflectors may give information about the type of sediment. However a certain number of boreholes to act as a control in the interpretation are needed. Sometimes a reflector splits and continues in two directions, for example a horizontal continuation and a dipping one. It is not always clear reading from the reflector amplitudes which of the two is the real continuation of the reflector. In such cases borehole information is usually a necessary requirement. In some cases however there are reflectors which cannot be correlated with the sedimentary sequence in the borehole. Slight differences in density can cause an acoustic impedance contrast. Deposits which do not show internal reflectors indicating the process of deposition cannot necessarily be resolved by seismics.
For instance in formerly glaciated areas in the Dutch sector thin till layers cannot be distinguished from periglacial sediments. Both sediment types may contain pebbles and both are relatively dense. In such cases borehole data are essential.

Photograph J.M.P.K. van Delft.

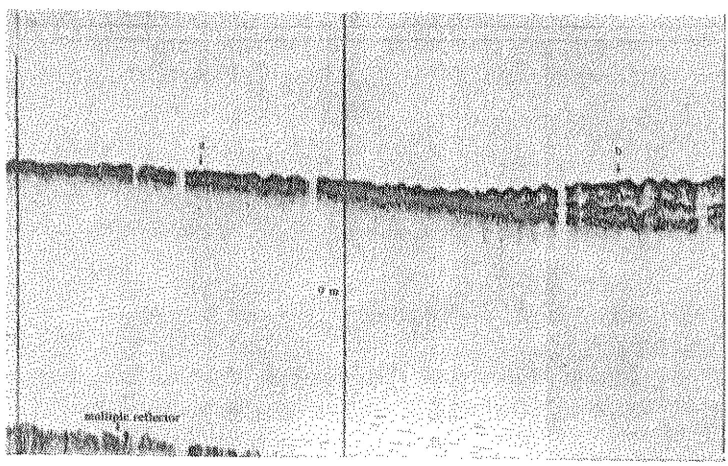


Fig. 8. High resolution seismic profile 3.5 kc (Sonia) of a gravel layer at the sea bed (a) with a thickness of >1 m. The signal is totally scattered and no reflectors from the underlying sediments are returned. In the sand cover overlying the gravel on the right reflectors are visible (b).

2.5.1 Gravel layers

The presence of gravel can give rise to scattering of the seismic signal, resulting in only limited penetration (Fig. 8). Gravel and boulders are seen as hyperbolas (Fig. 9).

Photograph J.M.P.K. van Delft

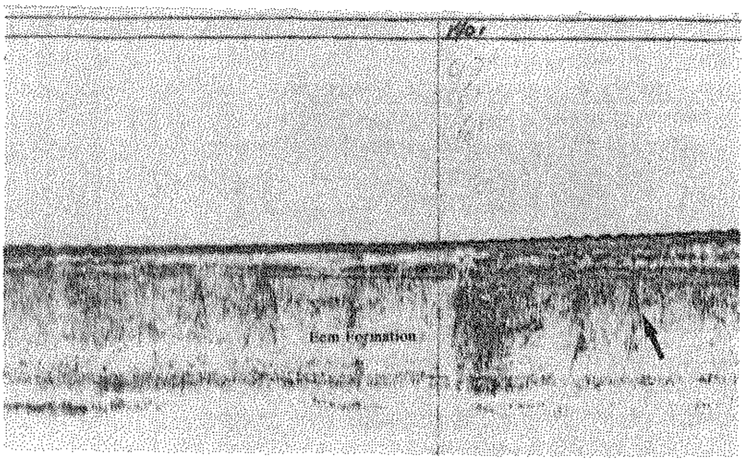


Fig. 9. High resolution seismic profile 3.5 kHz (Sonia) with hyperbolic reflectors (arrow) caused by the presence of boulders.

2.5.2 Gas-charged sediments

Concentrations of gas (methane) in sediments can cause acoustic transparent zones. Sedimentary structures can no longer be observed both in these sediments and in the underlying strata (Fig. 10) (Hempel, 1992). The sound velocities in these gas-charged sediments decreases to <1000 m/s and all acoustic energy is lost by absorption.

Photograph J.M.P.K. van Delft

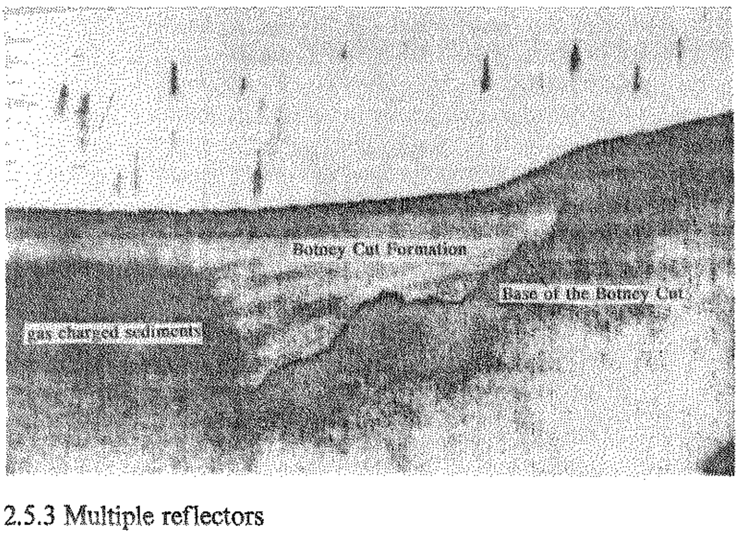


Fig. 10. High resolution seismic profile 3.5 kHz (Boomer) of gas-charged muddy sediments of the Late Weichselian Botney Cut and the Holocene Well Hole formations in the Botney Cut.

2.5.3 Multiple reflectors

A disadvantage of the high resolution 3.5 kHz systems is that in most cases in shallow water the maximum penetration is equal to the water depth. In deeper water the penetration is

mainly determined by the rock type and the acoustic power. In shallow water the sea bed reflection is reflected again by both the ships hull and the sea surface thus producing a great number of acoustic sources. Because of this phenomenon the two-way travel time in sea water (sound velocity 1500 m/s) between the ships hull/sea surface and the sea bed forms part of the profile without multiple reflections. The return of the second sea bed reflector causes a multiple reflection which thus masks all deeper reflectors and further penetration is thus limited (Figs. 7, 11 and 12).

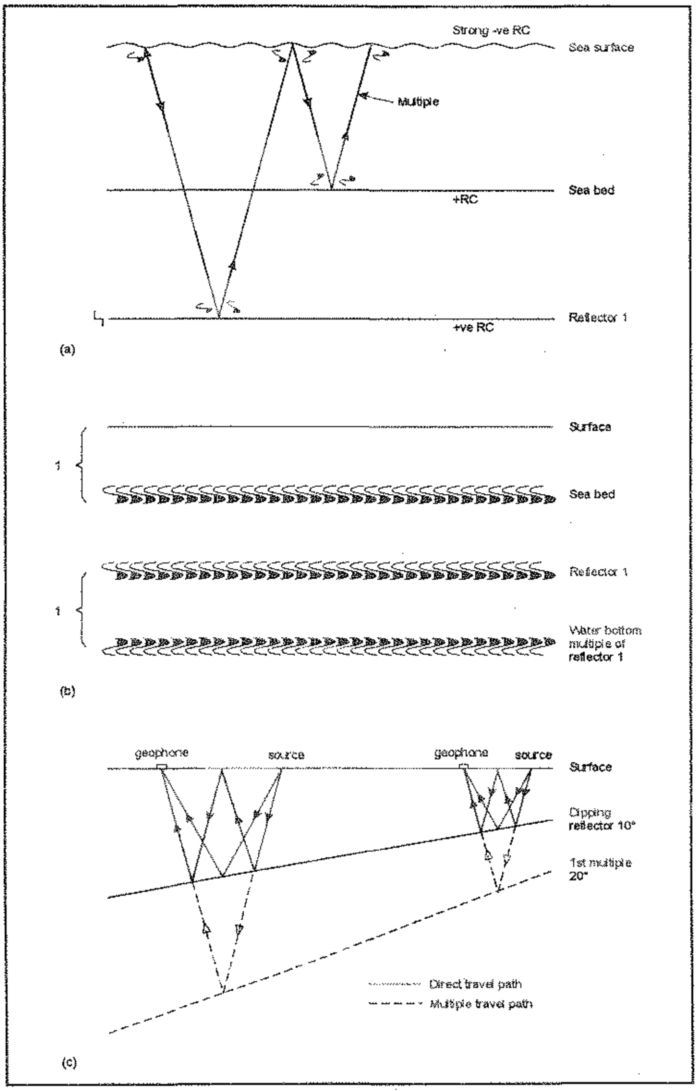


Fig. 11. (a) Scheme of water bottom multiple reflections. (b)The strong negative reflection coefficient of the air/water interface causes a polarity reversal of the downgoing multiple reflection. The positive sea bed reflection coefficient does not affect the reflection polarity; therefore, the recorded multiple reflection is opposite in polarity to that of the primary reflection. (c) The angle of dipping reflectors will increase 100% (after Badley, 1991)

Photograph J.M.P.K. van Delft

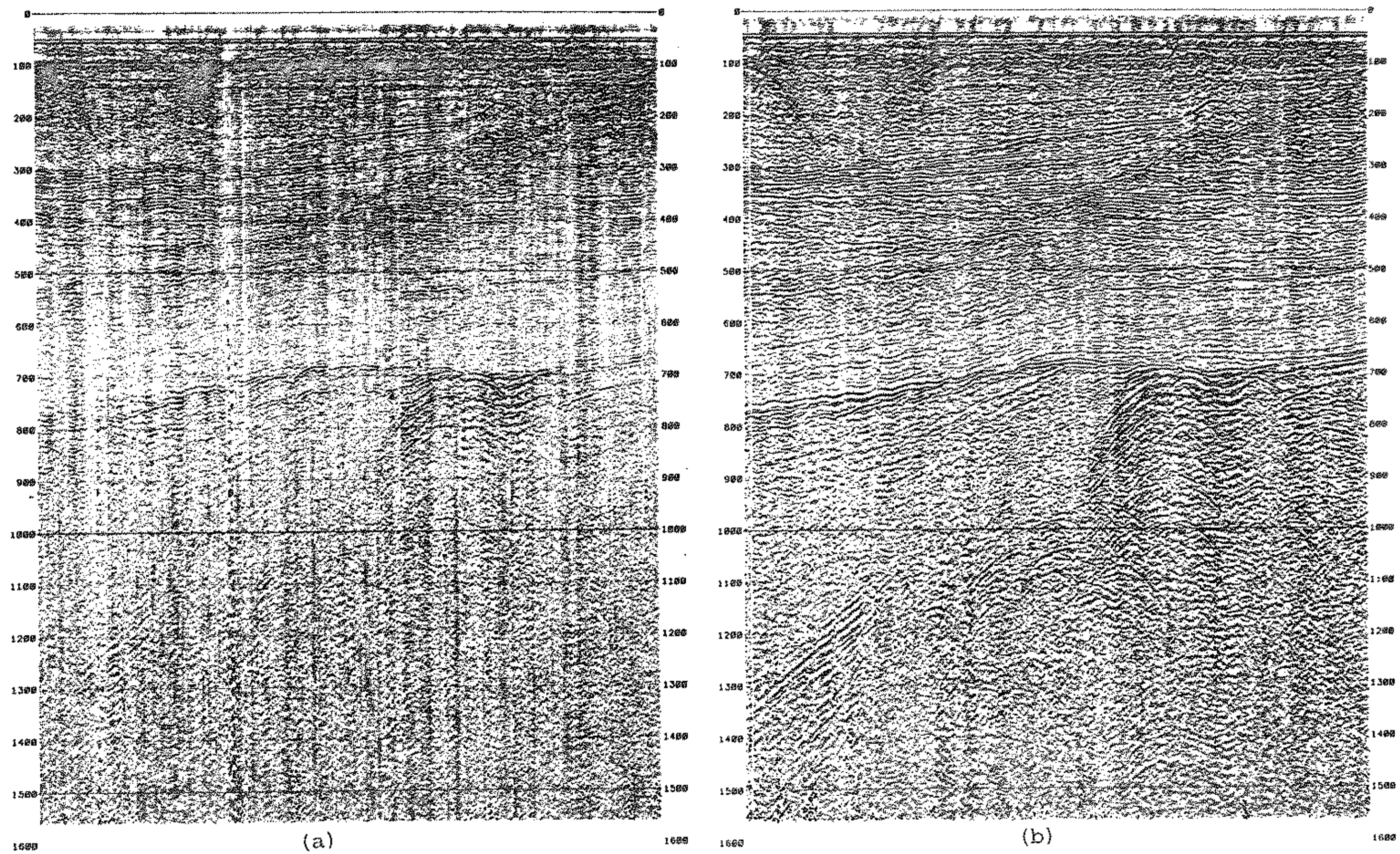


Fig. 12. *Seismic profile recorded with a multi-channel system (12 channels) north of the Frisian islands (line 9302, 1991). Source 10 cu./in. sleevegun. Filter settings 32-640 Hz. Processed with Promax processing system. Unprocessed (a) and processed (b). Depth in millisec.*

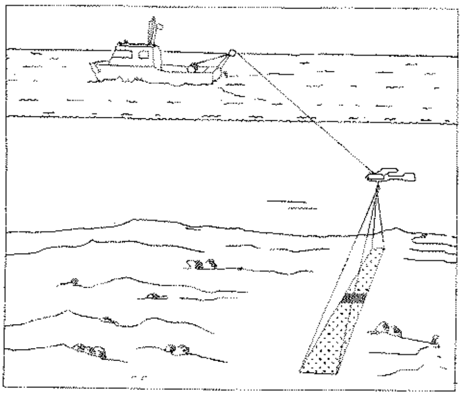
2.5.4 Underwater noise

Underwater noise caused by the ships engines, resulting in ship hull vibrations and/or cavitating of the propellers may cause disturbance on the seismic profile (Santiago & Carbo, 1992).

2.6 Seismostratigraphy

Seismic profiling enables one to obtain a registration of continuous profiles of the sea bed up to a certain depth. What in fact is obtained is a registration of acoustic impedance contrasts which, as explained, may not necessarily be related to significant lithostratigraphic boundaries. Thus significant lithostratigraphic boundaries do not always generate a reflector and conversely not every significant reflector represents a geological boundary. The units which can be distinguished on a seismic profile therefore are termed seismostratigraphic units. Regional correlation of these units however, taken in conjunction with data collected from boreholes forms the basis of understanding the main geological characteristics and structure of an area.

a



2.7 Side-scan sonar systems

Side-scan sonar techniques are used for mapping the sea bed morphology. The pulse generating techniques and data recording are similar to those of some seismic systems. Depending on the system, the frequencies which can be used range between 50 and 500 kHz, but most common is 100 kHz. A long narrow transducer, built in a "fish", is towed behind the ship at some distance above the sea bed transmitting high frequency signals simultaneously on both sides. The pulse length is very short ranging

b

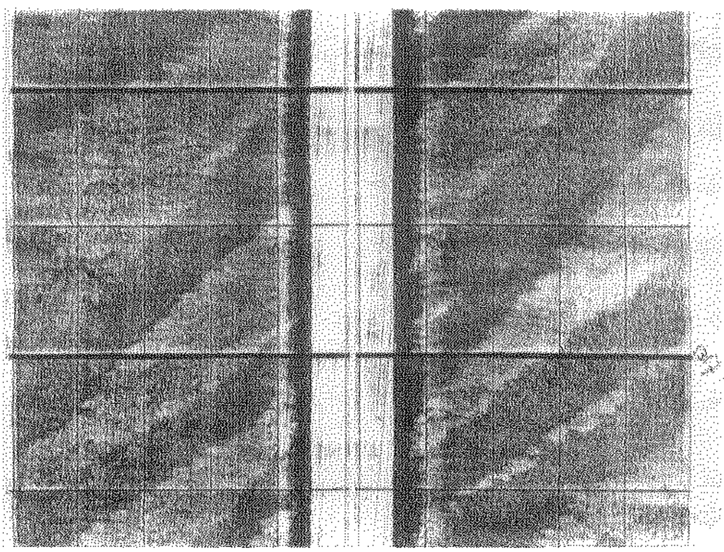


Fig. 13. A schematic drawing of an operating side scan sonar (a) and a record of an EG&G side scan sonar registered in the Cleaver Bank area (b). The light areas represent the occurrence of sand ribbons, the dark areas gravelly sand with current ripples.

from 0.1 msec to 0.25 msec. The resolution achieved can be less than 3 cm. The vertical beam angle depends on the system used and will be less than 45°, the horizontal angle generally < 2°. As the ship proceeds, successive transmissions scan the sea bed. The reflected signals registered on a recorder result in an acoustic image of the sea bed (widths from about 100 m up to about 100 km). The quality of the image depends on the ship's speed, the pulse repetition rate and the sea conditions (Fig. 13).

2.8 Sampling methods

2.8.1 Coring techniques

From 1968 up to 1990 many thousands of short cores were taken in the Dutch sector of the North Sea using several types of vibrocores. The first type of vibrocorer used was the so-called 'Zenkovitch'. This consisted of a rectangular base frame on which two vertical guide poles were mounted and a vibrator head which could move up and down. Two electrical vibrators were mounted in the vibrator head each with a frequency of 1500 rev./min. At the base of the vibrator head a steel barrel with a diameter of 7 cm and a variable length between 3 and 5 metres was mounted. The equipment was lowered to the sea bed and began operating as soon as the gear was in a stable position. High air pressure created in the barrel prevented sea water from entering the tube during the lowering of the equipment to the sea bed. During coring the air pressure increased even further due to the sampled material entering the barrel. Release of the pressure to only 1 atmosphere facilitated further penetration of the core barrel into the sea bed for further sampling. The core in the barrel is prevented from dropping out by a core catcher mounted just above the core bit. This prevents any loss of material during the hoisting of the equipment from the sea bed.
The average penetration was only 2 to 3 metres although at that time this was considered quite reasonable. The core quality was moderate. In most cases however sedimentary structures were destroyed. This was partly due to the vibrator frequency and partly to the high percentage of water in the core because some sea water was always sucked in.

In the late seventies an air hammer corer was developed by the RGD (Hoogendoorn, 1990). The frequency of the hammer was 700 blows per minute. This equipment gave a much better penetration, but the core quality was again only moderate.
In 1990 a hydraulic vibrocorer was designed by the RGD (Hoogendoorn & Kluwen, 1990). This corer has a vibrating frequency of 1750 revs./min. The diameter of the barrel can be varied from 7 to 10 cm, and the length from 5 to 6 m. The average penetration is 4 to 5 metres, and the quality of the core is excellent. From each core lacquer peels can be made and sedimentary structures are not destroyed. This vibrocorer has taken several cores in the glaciated area of the Dutch sector in order to obtain high quality samples for sedimentological and micromorphological studies.

2.8.2 Counterflush systems

The principle of the counterflush/airlift system is as follows: within the drill barrel an inner tube is mounted. At the top of the drill barrel an inlet for sea water is present. At the upper end of the inner barrel there is an air inlet. During drilling air under pressure is fed into the inner barrel changing the specific gravity of the water. The introduction of air results in a powerful water stream through the annular space. Water then passes through small holes in the core bit thereby loosening the sediment. Subsequently water enters the inner barrel and a

mixture of both water and loosened sediment passes through the barrel to the surface. The end of the inner barrel is connected with a flexible hose through which the sediment-loaded water is transported to the ship's deck.

In 1969 the Geodoff vibrocorer was developed by the RGD and Conrad Stork. This corer was heavy (6 tons) and in practice the average length of cores obtained was little less than obtained with the electrical vibrocorers. The head of the drilling department of the RGD, R. Hoogendoorn, altered the Geodoff into a system for counterflush/airlift. After emplacement of the equipment on the sea bed, samples up to 11 metres below sea bed can be collected in only twenty minutes. These samples are disturbed, but for the geological reconnaissance study of the Dutch sector of the North Sea hundreds of counterflush bulk samples of relative good quality have been collected. Representative samples have been taken at each metre and at any lithological change.

In 1972 the Geodoff MK II was built. This system has a number of technical advantages (clinometer, refinements to stability capacity and more pull-down power).
Since 1993 new drilling equipment, the Roflush, has become operational. Counterflushing down to several tens of metres is possible with this equipment. However to date only a few boreholes have been drilled with this relatively new equipment.

2.8.3 Straight flush systems

In addition to the sampling programme of the RGD, carried out in co-operation with the North Sea Directorate of the Ministry of Public Works, a great number of deeper well-cored boreholes varying from 40 to about 100 metres in depth have been drilled for offshore oil and gas exploration to predict rig leg penetration. Fugro B.V. has released most of these samples to the RGD after carrying out geotechnical analysis. Since 1968 hundreds of boreholes have been drilled for this purpose and the samples are stored in the RGD archive.
In 1986 two boreholes were drilled for the RGD by the Soil Survey vessel mv Mariner of Heerema. The boreholes, located in Dutch blocks E1 and E8 respectively, reached a depth of 150 m below the sea bed. Later, in 1989, a 100 m borehole was drilled in block A5 and a 195 m borehole in block F8. A 220 m borehole was drilled in block F18 by the Norwegian drilling vessel mv Bucentaur as part of an EC project.

The deeper well-cored boreholes generally use the straight flush drilling method. Drilling mud is injected under pressure through the core barrel to the sea bed and in so doing passes the core bit into the sediments. The mud rises up in the space between the drill pipe and the borehole and transports the sediments up to sea bed level. Sampling is done through the drilling barrel with a wireline system. A sampling tube is mounted at the end of a core hammer and lowered to the core bit. As soon as the sampling tube reaches the sediment below the core bit the tube is then hammered into the sediment. After a certain number of blows it is lifted. By this method high quality samples are obtained every one or two metres. The recovery during the drilling of boreholes for the RGD was about 0.40 m per metre.

2.8.4 Cone penetration test (CPT)

This method gives information about the in situ resistance of the sediments. A cylindrical rod with a conical tip is pushed into the sea bed at a constant penetration rate of about 20 mm/sec. which causes the sediments underneath the tip of the cone to be pushed aside. The

stress which is built up around the tip of the cone, depends on the deformation characteristics of the sediment layer. The signal of cone resistance, measured during the penetration into the sediments, is stored digitally and also registered and displayed versus depth. Additionally the sleeve friction, pore water pressure and inclination are measured. The data obtained are used for calculating the bearing capacity of the sea bed layers.
Most of the CPT information in the Dutch sector is collected by Fugro B.V. and is used by geologists to correlate between resistance and lithology. The CPT at sea is performed by Fugro-developed wireline systems which are lowered into boreholes. The resistance is measured at the base of the borehole at each interval to a maximum depth of 650 m below the drill floor. Another method is the lowering of a heavy frame from which the CPT is performed on the sea bed (Fig. 14).

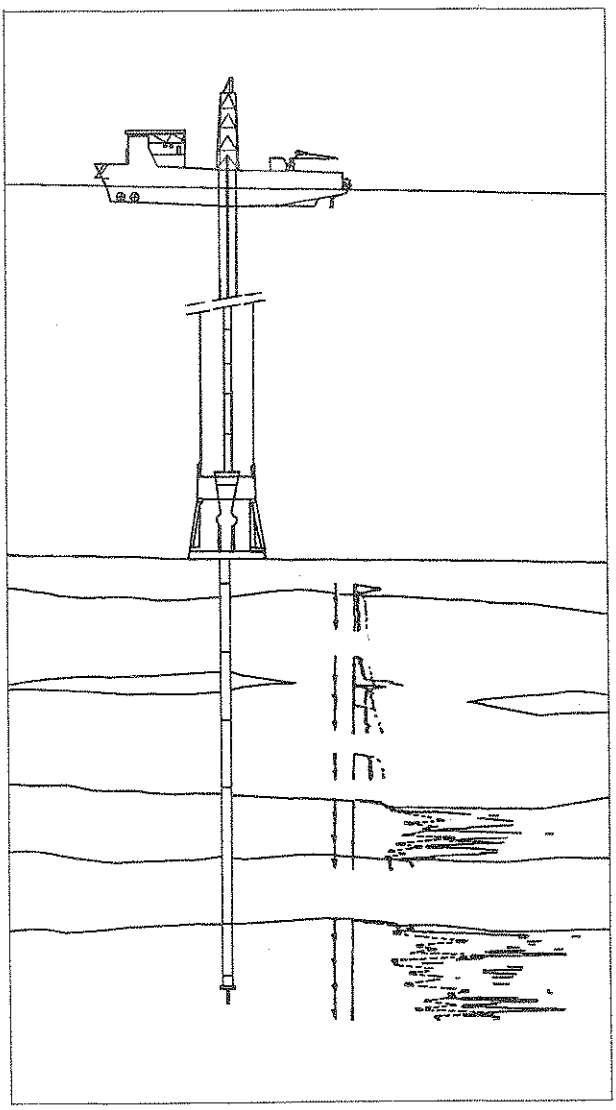


Fig. 14. The CPT system as operated by Fugro B.V. at sea bed. Higher resistance indicates increase of sand.

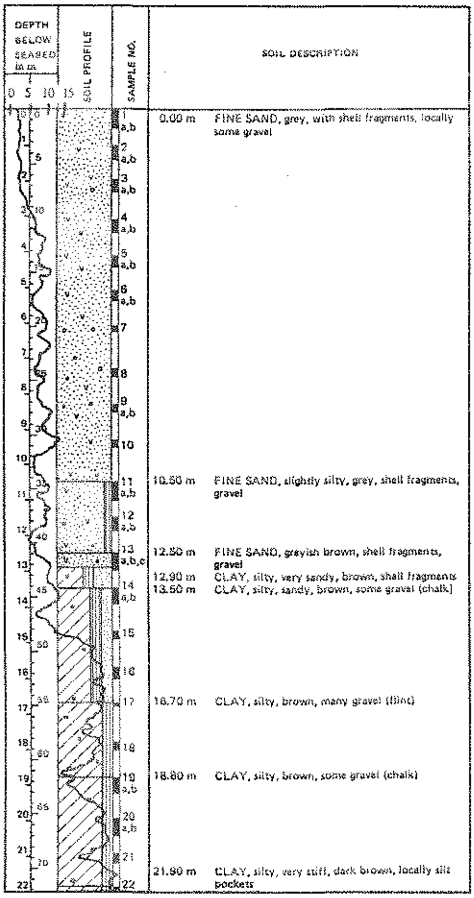


Fig. 15. Record of a gamma log as measured in a borehole. The transition from sand (Holocene) into clay (Dogger Bank Formation) is clearly visible from the increase of gamma radiation in CPS (counts per second).

2.8.5 Natural gamma-ray logging

After completion of straight flush drilling, the boreholes are logged. A gamma receiver is lowered down the barrel. All sediments show gamma radiation due to the presence of natural emitters like uranium, thorium and potassium, and which are dissolved in the pore water or adsorbed onto grain surfaces. The radiation tends to be highest for the older, most compacted clays and lower for younger, less compacted marine clays and fresh water clays. The radiation of quartz sands is very low.

From the gamma ray curve not only clays and sands can be distinguished, but also an increase or decrease of silt and/or clay content in sandy sediments (Threadgold, 1980) (Fig. 15).

2.8.6 Positioning systems

The accuracy of the positioning system used is of great importance in the execution of geological surveys at sea. Firstly the positioning system used during the seismic survey must allow the vessel to return to the same position for sampling or coring. Secondly, it is necessary to survey seismic lines over certain borehole positions.

Since 1968 radiographic positioning systems have been used for geological surveys and these have progressively improved. The accuracy of the navigation systems in the Dutch sector of the North Sea, the main chains Decca 9B and 5B, is accurate to about 50-100 m. In 1972, and in the area south of 53°N, the Decca main chain 2E was introduced with an accuracy of 20-50 m. After 1976, Hifix 6 was used in the southern part of the Dutch sector while in 1987 a North Sea covering system became operational; the Hyperfix Terschelling chain for the northern part of the North Sea and the Hyperfix Thames chain for the southern part. The accuracy of this system is 5 m.

The highest accuracy with radiographic positioning systems is obtained during daylight. During evening and night the so-called skywave (lowering of the ionosphere) can disturb the radiosignals and result in less accurate positioning measurements.

Since 1992 Diffential Geosatellite Positioning Systems (DGPS) which have a continuous accuracy of about 1 m have become operational (Fig. 16).

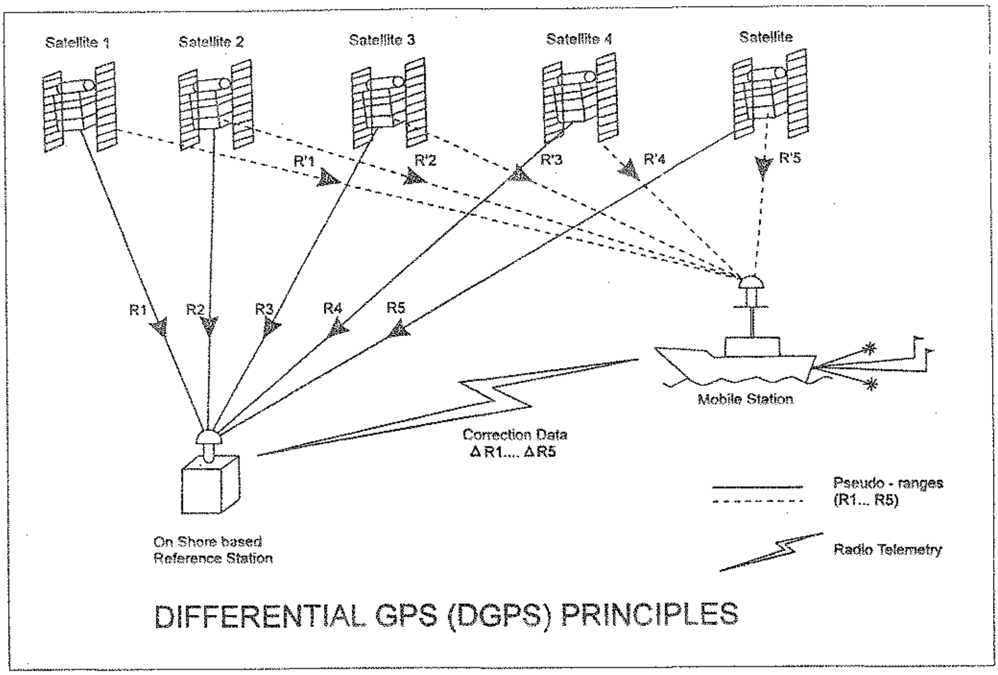


Fig. 16. The Differential Geosatellite Positioning Systems (DGPS).

2.9 Laboratory analysis

For the present study the scientific laboratories at RGD and institutes of the universities of Amsterdam, Delft, Groningen and Utrecht have carried out a great number of analyses on North Sea samples.

- Pollen (RGD)

  Pollen records provide an insight into the palaeoclimatic conditions during deposition of the sediments in glacial and interglacial times. From the pollen record a relative age can often be deduced. The record of pre-Quaternary pollen carried by rivers or ice sheets from older rocks gives evidence of the provenance of the sediments. For example in the North Sea a distinction can be made between sediments derived from Scandinavia (Tertiary and Mesozoic pollen) and those from the British Isles (Palaeozoic and Mesozoic pollen). Many samples from boreholes in the Dutch part of the North Sea have been analyzed.

- Foraminifera (RGD)

  Analysis of foraminifera present in sediments have been of great value in determining their marine character. It is not always possible to recognize marine sediments when other indicators like marine molluscs are lacking. In addition to indicating marine and non-marine environments, the analysis provides information on water temperature during deposition of the foraminifera; for example it has been possible to distinguish foraminifera associa-

tions in several zoogeographic zones such as high, middle and low arctic, arctic to boreal and high, middle or low boreal (Feyling-Hanssen, 1955).

- Diatoms - ostracods (RGD)

  Diatoms and ostracods in sediments provide data on the environment of deposition e.g. lake, fluvial and marine deposits contain specific diatom and ostracod assemblages. Changes in the environment are immediately reflected by the flora and fauna.

- Mollusca (RGD)

  The mollusc content of the sediments also gives data concerning the marine or non-marine depositional environment and also the stratigraphy. In addition mollusc associations provide evidence of both climatic and environmental conditions such as water depth and salinity.

- Heavy minerals (RGD)

  Fluviatile deposits from the Baltic rivers, the German rivers Elbe and Weser and the rivers Rhine and Meuse respectively can be distinguished on the basis of the heavy mineral assemblages of sand samples obtained from various boreholes. It is also possible to distinguish between glacially reworked fluviatile sands and non-reworked fluviatile deposits.

- Grain size analysis (RGD)

  Grain size analysis is of importance in establishing the sedimentary environment. Modern equipment used in such analysis is the Malvern Particle Sizer (Laser Counter).

- Gravel analysis (RGD)

  Gravel types in the glacial deposits of both British and Scandinavian origin may be distinguished on the basis of rock type.

- ^{14}C dating (Centre of Isotopic Research, University of Groningen and R.J. Van de Graaff Laboratory, Utrecht University)

  Several samples of wood, peat and foraminifera have been dated by ^{14}C methods both classical and Accelerator Mass Spectrometry (AMS) to obtain an insight into the age of Weichselian periglacial and glaciomarine deposits.

- Organic matter (University of Delft)

  To distinguish between Saalian and Weichselian glacial sediments their organic content has been analyzed by both chromatography (GC) and gas chromatography mass spectrometry (GC-MS) methods.

- Scanning Electron Microscopy (SEM) (RGD)

  With the assistance of Scanning Electron Microscopy photographic differences can be detected between glacial, periglacial and fluviatile sediments.

Thin sections (Department of Physical Geography and Soil Science, University of Amsterdam)

Information into both the depositional environment and post-depositional processes has been obtained by examination of microstructures recognized in 'mammoth-sized' thin sections of various tills and glaciolacustrine sediments.

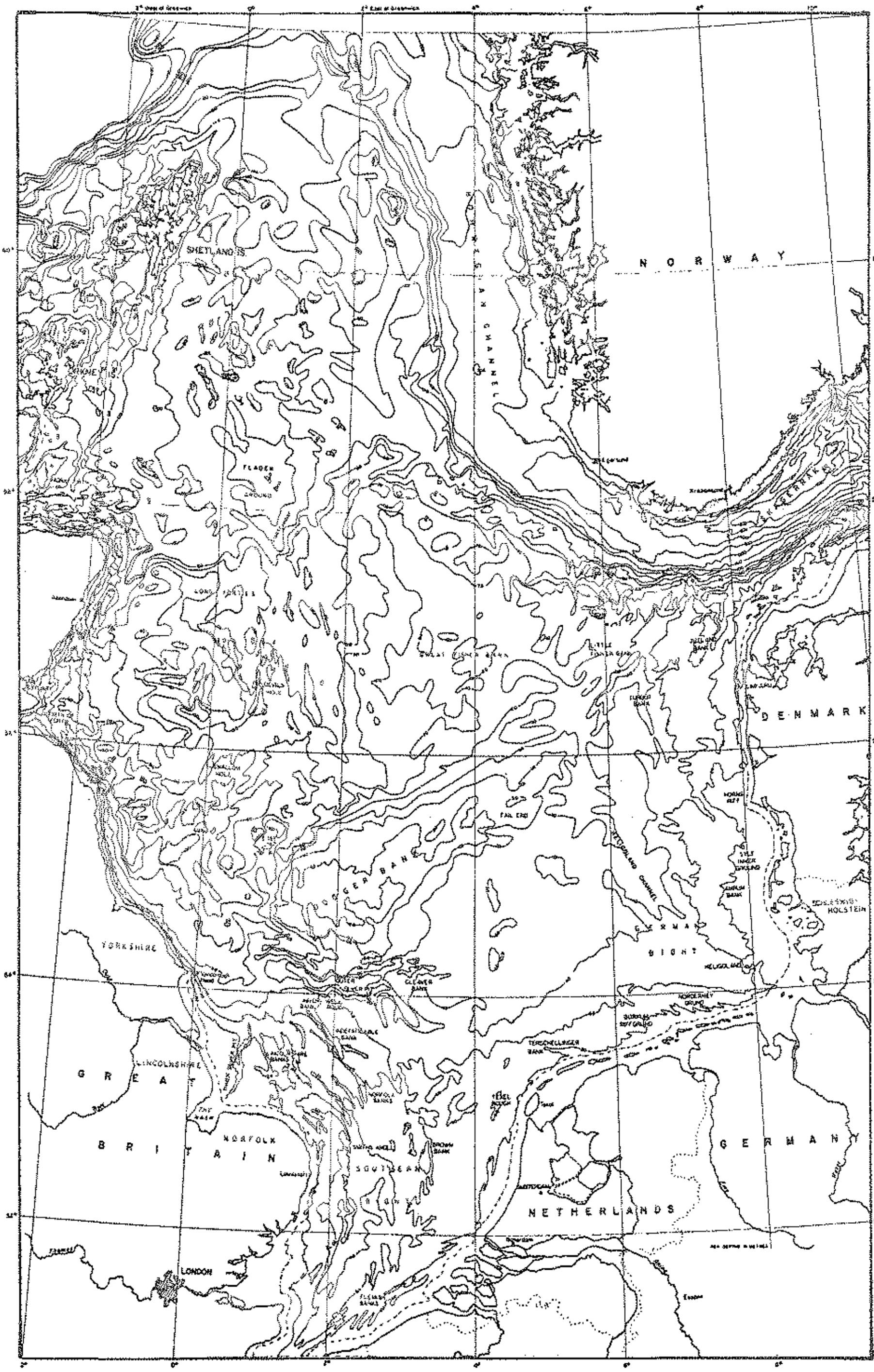


Fig. 17. Bathymetry of the North Sea; isobaths at 10 m intervals.

Chapter 3

Pre-Elsterian glaciations

3.1 Introduction

Several deep boreholes in the Dutch sector of the North Sea showed indications of evidence for pre-Elsterian glaciations during which ice sheets entered the North Sea or gave rise to cold conditions (Zagwijn, 1985, 1992). The cold conditions are reflected in the foraminiferal and molluscan faunas and/or the pollen assemblages. Correlations have been made with data collected from surrounding land areas.

The depth of boreholes and samples are given in metres below Mean Sea Level (MSL). The lower (deeper) sample is quoted first and the upper (shallower) sample second. For the location of boreholes, see Table 1 and Fig. 19.

3.2 Tiglian C4c glacial phase and Eburonian Stage

In the Dutch sector of the North Sea the oldest deposits postdating the cold Praetiglian Stage, so far sampled in our boreholes, and indicating a cold Pleistocene phase are marine deposits probably dating from the Late Tiglian (C4c). They have been found in the well-cored borehole F8-6, in which a stiff marine clay referred to the IJmuiden Ground Formation occurs between 244.60 m and 242.50 m below MSL (Cameron et al., 1984a and 1984b). The foraminiferal content of the clay represents a rich, high arctic, fauna poor in species. The fauna is dominated by *Elphidium excavatum f. clavata*. Other species are *Buccella frigida* and *Elphidium asklundi*. Between 242.56 m and 242.50 m a relatively high percentage of *Nonion orbiculare* is present (Neele, 1991a). Molluscs are absent (Pouwer, 1991a). Probably this clay can be correlated with the cold marine Baventian clay from the Tiglian C4c phase in the cliff section at Easton Bavents, on the Suffolk coast England (see below). In borehole F8-6 the stiff clay is overlain (between 242.50 m and 157.14 m) by a fine- to coarse-grained sand deposit (Winterton Shoal Formation) poor in calcium carbonate and deposited by the German rivers Elbe and Weser, probably during the Menapian Stage.

In borehole G16-22 a deposit of stiff clay is present between 260 m and 253 m below MSL. Based on the evidence of dinoflagellate cyst analysis the clay probably settled in a shallow marine low salinity environment during the Late Tiglian and Early Eburonian. Evidence of age is provided by palaeomagnetic measurements, which indicate, between 256 m and 255 m below MSL, reversed polarity and at 257.75 m and 257 m below MSL normal polarity. The normal polarity may represent the upper part of the Olduvai normal event in the Matuyama reversed epoch (Sha et al., 1991). The pollen content of the clay is poor, indicating cold climatic conditions (De Jong, 1991). The foraminiferal fauna is poor to very poor, again pointing to arctic conditions with species such as *Elphidium albiumbilicatum, Elphidium excavatum f. clavata* and *Nonion orbiculare* (Neele, 1991b). This clay, deposited in a prodelta,delta-front to mouth bar environment is referred to the IJmuiden Ground Formation and the sediments can probably be correlated with the Tiglian C4c cold phase. Neele (1991b) however has suggested that because of the absence of the foraminiferal species *Elphidiella hannai* this clay deposit is post-Tiglian. The pollen spectrum shows a transition to a warmer phase at the top of the clay and the base of the overlying sand between 252.13 m and 242.04 m below

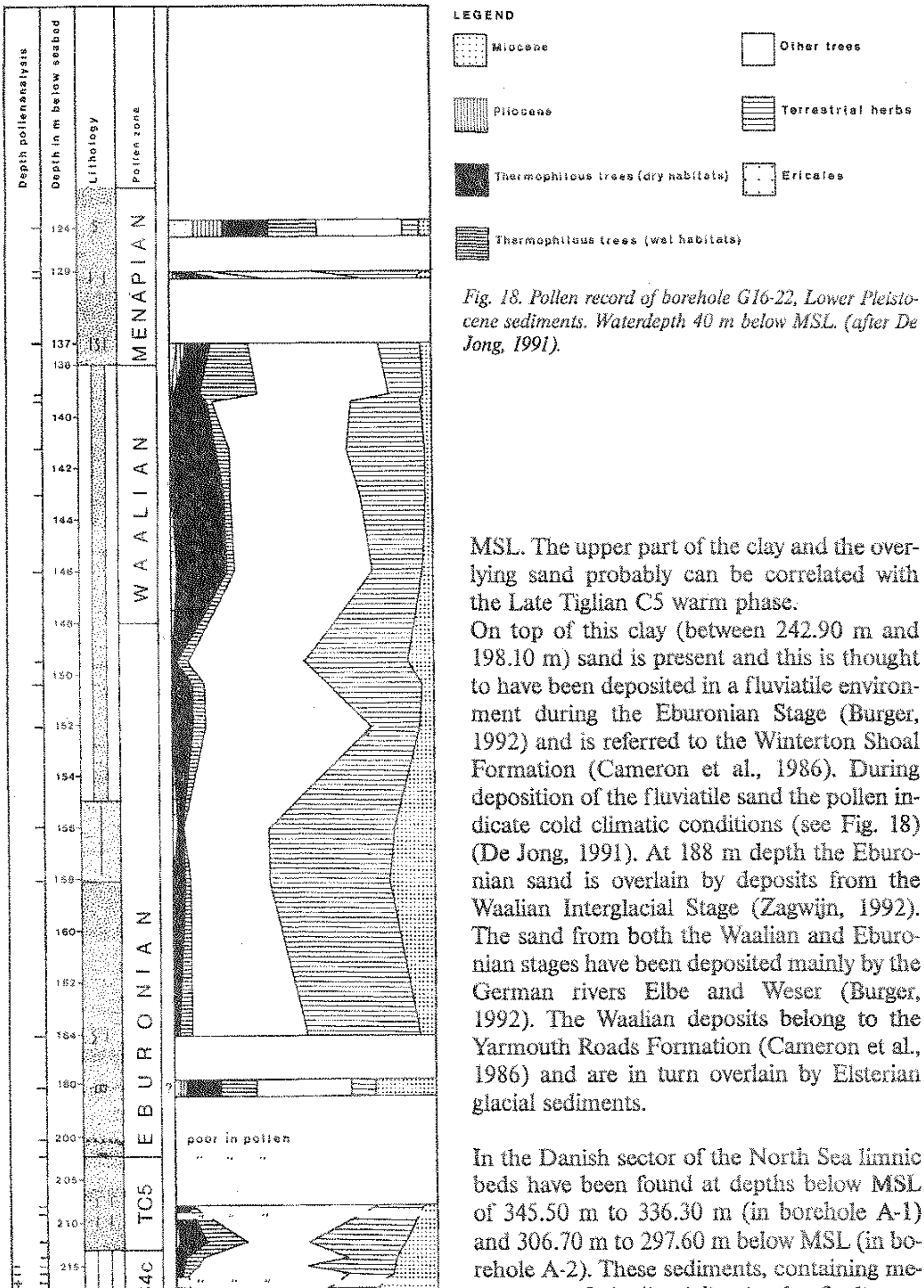


Fig. 18. Pollen record of borehole G16-22, Lower Pleistocene sediments. Waterdepth 40 m below MSL. (after De Jong, 1991).

MSL. The upper part of the clay and the overlying sand probably can be correlated with the Late Tiglian C5 warm phase.

On top of this clay (between 242.90 m and 198.10 m) sand is present and this is thought to have been deposited in a fluviatile environment during the Eburonian Stage (Burger, 1992) and is referred to the Winterton Shoal Formation (Cameron et al., 1986). During deposition of the fluviatile sand the pollen indicate cold climatic conditions (see Fig. 18) (De Jong, 1991). At 188 m depth the Eburonian sand is overlain by deposits from the Waalian Interglacial Stage (Zagwijn, 1992). The sand from both the Waalian and Eburonian stages have been deposited mainly by the German rivers Elbe and Weser (Burger, 1992). The Waalian deposits belong to the Yarmouth Roads Formation (Cameron et al., 1986) and are in turn overlain by Elsterian glacial sediments.

In the Danish sector of the North Sea limnic beds have been found at depths below MSL of 345.50 m to 336.30 m (in borehole A-1) and 306.70 m to 297.60 m below MSL (in borehole A-2). These sediments, containing megaspores of *Azolla tigliensis*, the freshwater gastropod *Valvata piscinalis*, and seeds from plants related to lacustrine environments

which have been correlated with the Tiglian C4c cold phase as a regressive deposit (Bertelsen, 1972).

The near presence of ice in the North Sea during the Early Pleistocene Tiglian C4c phase was suggested from evidence which was found in the erosive cliff-section at Easton Bavents on the Suffolk coast of England. Here marine deposits, dated as Baventian Stage, contain foraminifera species dominated by *Elphidiella hannai*. Other species include *Elphidium excavatum f. clavata, Elphidium frigidum, Elphidium pseudolessonii* and *Ammonia beccarii*. This assemblage suggests that the main clay horizon probably accumulated in a glacial sea. Although A. beccarii is regarded as an indicator of interglacial conditions, the authors (Funnell & West, 1962) concluded that the foraminifera suggest a transition from interglacial to glacial climatic conditions.
The most common mollusc species is *Macoma calcarea*. Other less common species include *Arctica islandica* and *Tridonta montagui*. The molluscs indicate an intra-littoral to sub-littoral deposit (Norton & Beck, 1972). The present known distribution of *Macoma calcarea* is low-arctic/high-boreal (Meijer, 1993).
The pollen assemblage contains mostly Ericales and Gramineae indicating that glaciers were present not far from East Anglia during pollen sub-zone L4b (Funnell & West, 1962). Heavy mineral analysis (Solomon, 1962) from the Baventian clay exhibit an assemblage containing a high proportion of alkali amphibole and also sphene which seems to indicate that the deposits mainly consist of outwash material from a northern ice sheet (Hey, 1976; 1991). A similar assemblage is found in the Elsterian North Sea Drift. Much further north of Easton Bavents, in the Yorkshire Wolds, Catt (1982) found remnants of glacial deposits with an erratic content which, he suggested, were deposited during the Baventian Stage.

Gibbard et al., (1991) correlate the Baventian Stage with the Tiglian C4c phase. During this phase of the Tiglian, cold climatic conditions prevailed (De Jong, 1988; Zagwijn, 1985). On the basis of pollen, Funnell & West (1962) placed the sand underlying the Baventian clay in the temperate Antian Stage.
In Tiglian deposits (Beerse Member) in the southern part of The Netherlands, Vandenberghe & Kasse (1989) and Kasse (1993) have found periglacial structures like ice-wedge casts and frost cracks which are supposed to have been formed during the Tiglian C4c stage (Beerse Glacial).

3.3 Menapian Stage

Other indications of pre-Cromerian Stage deposits in the Dutch sector of the North Sea are found in borehole L10-6. In this borehole fluviatile sediments are present below Cromerian III/IV deposits (Zagwijn, 1977) between 129.35 m and 80.35 m below MSL. They have been deposited under cold climatic conditions during the Menapian Stage. The pollen assemblage contains a mixture of Pleistocene and Tertiary pollen which have been derived from fluvio-glacial deposits. Near the base of the borehole, at 129.35 m below MSL the pollen assemblage contains a high percentage of herbaceous pollen also suggesting cold conditions. The heavy mineral content indicates that the sediments have been deposited by the German rivers Elbe and Weser. The sediments are referred to the Yarmouth Roads Formation.

In borehole G16-22 fluviatile sand is present between 179 m and 149 m below MSL. The pollen record indicates the sand has been deposited under cold climatic conditions (De Jong,

1991) and is correlated with the Menapian Stage. This sand also has been supplied by the German rivers Elbe and Weser and thus is referred to the Yarmouth Roads Formation.

In the Norwegian sector west of Bergen, the 219 m deep (below MSL) Troll borehole (8903) proved three tills. Between 508 m and 528 m below MSL a matrix-supported till interbedded with thin beds and laminae of sorted sand was proved. This till was dated approx. 1.1 million years BP (Sejrup et al., 1994) and represents the Fedje Glaciation (named after a small island north of Bergen). The till overlies Oligocene deposits. From a seismic survey run over the borehole location together with lines run both parallel and at right angles to the Norwegian coast it is apparent that the till sheet occurs over a length of more than 220 km along the coast. Far to the north in the Norwegian Sea near Haltebanken in a 130 m deep borehole (DR88/30) at a depth of 368 m to >372 m below MSL a dark greyish-brown diamicton was proved containing Mid-Norwegian granites and gneisses. The diamicton is regarded as a till deposited by a grounded glacier of a Scandinavian ice sheet. The till occurs below the Matuyama/Brunhes reversal (0.76 my) and is also dated approx. 1.1. million years (Haflidason et al., 1991). It is probable that both tills in the eastern part of the Norwegian sector were deposited during the Menapian Stage.

In the British sector, in borehole 79/08, a stiff to very stiff, dark grey to brownish-grey clay with silt laminae occurs between 189.50 m and 151.50 m below MSL. Pollen analysis shows that the clay was deposited during a glacial stage; strong fluvioglacial factors appear to have been at work. The pollen spectra in the overlying interglacial deposits are not indicative of a specific interglacial except for the presence of Tsuga which suggests an Early Pleistocene age. De Jong, (1981a) suggests, based on correlations with other boreholes (J14-1 and K1-10), that the clay must be considered as having been deposited during the Menapian Stage.

In Denmark a sequence consisting of 5 m of fluvioglacial deposits overlying an approximately 5 m thick till layer occurs at Harreskov in Jutland. They underlie Cromerian limnic sediments and because of their stratigraphic position are dated as Menapian (Andersen, 1967; Sjörring, 1983; Houmark-Nielsen, 1987).

3.4 Cromerian Stage

Deposits dating from the Cromerian 'Complex' Stage are found in the Dutch sector in borehole E1-10 drilled to a depth of 173.63 m below MSL on the south-east flank of the Dogger Bank. In this borehole very fine, grey, slightly silty sand with sporadic clay laminae and organic matter has been sampled between 153.20 m and 130.30 m. Pollen analysis point to glacigenic influences; pollen traces are wholly of Scandinavian origin with no influence of 'British ice' (De Jong, pers. comm.). No foraminifera or molluscs are present (Neele, 1986b). Between 138.60 m and 130.30 m the sand contains some shell fragments which apparently are reworked (Sliggers & Meijer, 1987). Zagwijn (1986) suggests that the age of this bed is Cromerian and probably belongs to Glacial B or A. This sand layer is overlain by a marine bed which contains an arctic to boreal foraminiferal fauna (Neele, 1986b). The molluscs present indicate temperate climatic conditions prevailed with important fluvial influences (Sliggers & Meijer, 1987). Pollen analysis indicates cool to warm climatic conditions. Zagwijn (1986) suggested that the age of this bed is probably Cromerian III at the base and Glacial C towards the top. This unit, which is overlain by Elsterian deposits, belongs to the Yarmouth Roads Formation.

Near borehole E1-10, borehole E8-6 in block E8 was drilled to a depth of 183.50 m below MSL. In this borehole a clay bed is present between 152.50 m and 147.50 m in which a high arctic foraminiferal fauna is found with species dominated by *Elphidium excavatum f. clavata, Nonion orbiculare*, and *Elphidium ustulatum* (Neele, 1991b). The pollen record also shows evidence of cool climatic conditions (De Jong, pers. comm.). The glacial, laterally equivalent, sand deposit in borehole E1-10 is, however, non-marine and it is suggested that a coastline lay between these two boreholes at this particular time. This 'cold' deposit is overlain by both marine and non-marine deposits. Between 115.75 m and 109.20 m fluviatile deposits with probably some tidal influence are present. The deposit contains the mollusc *Valvata goldfussiana* which is of Cromerian II age or even older (Zagwijn, 1986; Pouwer, 1991a; Meijer & Preece, 1994).

North of the above locations, and in boreholes 74/10 and 74/12 in the British sector, a deposit of brown to olive-grey, firm, poorly sorted, dominantly matrix-supported gravelly sandy mud is present with no faunal remains or obvious bedding structures. The thickness of this bed is 2 to 3 m. The authors (Stoker & Bent, 1985) regard these sediments as some form of lodgement till which may be the preserved remnants of a previously more extensive subglacial till cover, or a local ice-grounding point. The pebble composition points to a British origin. The subglacial deposit is overlain by proximal glaciomarine sediments. The sediments of both glacial and glaciomarine facies belong to the Aberdeen Grounds Formation of Tiglian to Late Elsterian age and occur just above the Brunhes-Matuyama boundary. The Aberdeen Grounds Formation is overlain by the Ling Bank Formation which contains a rich interglacial marine fauna and flora including megaspores of *Azolla filiculoides*. The age of the Ling Bank Formation is Holsteinian. The glacigenic sediments do not contain evidence for any involvement of a Scandinavian ice sheet (Stoker & Bent, 1985). This till was deposited during the Menapian Stage or during the Early Cromerian Stage. The authors suppose that the ice-margin was very similar to that envisaged for the Late Weichselian ice sheet.

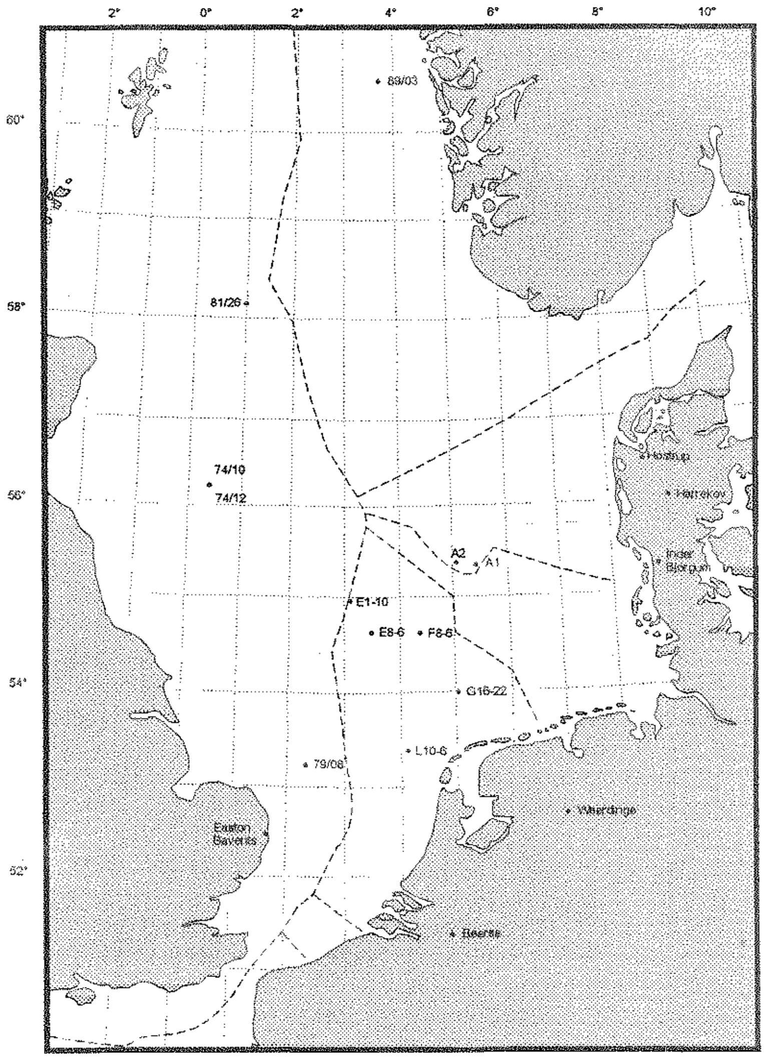
In borehole 81/26 in the Fladen Ground area of the British sector, a diamicton was present between 280 m and 268.55 m below MSL. The bed can be divided into two subzones. Subzone F1 consists of coarse sand, gravel and pebbles with deformation structures. The upper part of this bed is interpreted as of glacial marine origin. Subzone F2 possibly represents a shallow, proximal glaciomarine facies.
Based on amino acid datings and the occurrence of the bed just below the Brunhes/Matuyama boundary the authors (Sejrup et al., 1987; Sejrup et al., 1991) suggest that the age of the glacial sediments is Early Cromerian (850 ka), although it is possible that the age is Late Bavelian (Table 6).

Evidence for 'cold' deposits on land during the Cromerian Stage were found in the eastern Netherlands near Emmerschans. Here fluvioglacial sands, the 'Weerdinge Beds', are regarded as having been deposited close to an ice margin during the Cromerian Glacial C (Ruegg & Zandstra, 1977).
Fig. 19 shows the positions of the boreholes mentioned in the text.

3.5 Conclusions

In a number of boreholes in the British, Danish, Norwegian and Dutch sectors of the North Sea sedimentary, palaeomagnetic, faunal and floral evidence has been found for at least two Lower Pleistocene glaciations. The occurrence of glaciomarine sediments and tills of the

Fig. 19. Map showing the position of sites and boreholes recording Early Pleistocene 'cold' sediments.



Cromerian 'Complex' Stage in the British sector of the North Sea and tills of the Menapian Stage in the Norwegian sector provide evidence that these sediments have been widespread. This supports the supposition that there has been Early Pleistocene ice in the North Sea during at least two pre-Elsterian stages.

Indications of cold climatic conditions in the Dutch sector are found only in deeper boreholes at depths ranging between 220 m and 143 m below MSL. It can be demonstrated that fluviatile or near-shore sediments were deposited during the Late Tiglian cold phase C4c, the Eburonian and the Menapian cold stages. In a borehole on the south-east margin of the Dogger Bank glacigenic deposits were found which probably date from the Cromerian B or A glacial phases.
The lack of more deep well cored boreholes and the great distance between them make reliable correlations very difficult to establish with these early glaciations.

Chapter 4

The Elsterian glaciation in the Dutch sector of the North Sea

4.1 Introduction

The first glaciation in the North Sea from which abundant glacial sediments and features are preserved is the Elsterian Stage. The most striking feature of this glaciation is the occurrence of a complex system of deeply eroded anastomosing valleys and isolated oval depressions in the southern North Sea in a broad zone between 53°N and 56°N. The valleys have been eroded into pre-Elsterian deposits. The zone containing depressions continues towards the west into the British sector (Cameron et al., 1986; Jeffery et al., 1989; Cameron et al., 1992). Towards the east their presence has been proved from the northern Netherlands through northern Germany into Poland (Mojski, 1985, 1993) and they are also present in the Irish Sea (Wingfield et al., 1990).

The valleys in the Dutch sector of the North Sea have been mainly mapped from a regular and dense pattern of north-east/south-west and north-west/south-east seismic lines. The valleys appear to occur within the maximum ice limit of the Elsterian glaciation and mainly trend north-north-west/south-south-east. Because most of the seismic lines cross the valleys at an angle, it was decided to also run a multi-channel seismic line along the axis of one of the valleys. A difficulty in interpreting the valleys from seismic lines is that the shoulders are not always clearly defined or visible. They occur on the upper part of the profiles where they are often obscured by multiple reflections from the sea bed. Even on processed profiles the upper multiples are still present. Most of the valleys have steep slopes in cross section with angles ranging between 5° and 25° in the Dutch sector of the North Sea (Joon, 1987) and up to 55° on land in northern Germany (Küster & Meyer, 1979). From the longitudinal profile it is clear that the base of the valley is not flat but shows sub-basins and thresholds. In the valley shown in Fig. 22 elevations of thresholds of 180 m were observed. The valleys vary in width between <1 km and 23 km and are in general 100 m to 250 m deep, and exceptionally a depth of about 510 m below MSL is reached.

The valleys are most numerous between 53°N and 54°N. South of 53°N comparable valleys are not found. On two seismic lines between 52°50' and 53°N and approx. 02°27' E, some valleys up to 50 m deep and several kilometres wide are present incised into the Yarmouth Roads Formation. They probably are associated with the southern end of deep valleys north of the 53°N (Cameron et al., 1984b). Between 54°N and 56°N only isolated valleys are present.

The depth of boreholes and samples are given in metres below Mean Sea Level (MSL). The lower sample is quoted first and the upper sample second. For the location of boreholes, see Table 2 and Fig. 23.

4.2 Previous work on valleys in the countries surrounding the North Sea

4.2.1 Denmark

The study of glacial valleys in Denmark dates back to the end of the last and beginning of this

century (Ussing, 1899, 1907), and these features can be regarded as a classic type-locality for tunnel valleys.

Most of the glacial valleys in Denmark are polygenetic. Probably they were formed initially during the Elsterian glaciation, but were deepened again during the later Saalian and Weichselian glaciations.

Ussing (1904, 1907) discussed large valley systems in Jutland which could be divided into two groups: late glacial meltwater outlets in front of an ice margin and "fjord valleys". The latter are regarded as older and eroded by subglacial streams. Because the floor of the valleys lay considerably lower than the surface of the adjoining plains, Ussing suggested that the valleys must have been formed by water under pressure in "tunnels" which had the capacity of forcing its way uphill. This also could be the reason for uneven profiles in the valleys with elongated lake basins with shallow thresholds between them. Madsen (1921) changed the name "fjord valleys" to tunnel valleys.

Hansen (1971) suggested that not all tunnel valleys in Denmark were eroded by meltwater, but in some cases erosion by ice had taken place.

Sjörring (1979) also suggested that not all these valleys are tunnel valleys, but comprised different geomorphological elements some of them representing preglacial or proglacial stream channels which are locally overdeepened by advancing ice. Berthelsen (1972) is of the opinion that erosion by ice lobes would occur at locations with local variations in permafrost distribution.

Bruun-Petersen (1987) published a map of south-west Jutland indicating the presence of Holsteinian Interglacial sediments in a valley system. According to P.B. Konradi of the DGU (pers. comm.) the sediments are marine and at many places are underlain by Elsterian glaciomarine deposits. This confirms the view held by Knudsen & Penney (1987) who studied the Tornskov borehole in southern Jutland. Here the lowest zones (between 95 m and 80 m) contain arctic foraminifera indicating that marine conditions first reached the area during the Late Elsterian. The overlying marine sediments contain a Holsteinian Interglacial foraminiferal fauna.

4.2.2 Northern Germany

The Elsterian valley systems in northern Germany have been discussed by a great number of authors since the end of the last century. Gottsche (1897) described deep glacial valleys in the area near Hamburg. Niedermayer (1965), Grube (1979), Küster & Meyer (1979), Hinsch (1979), Ehlers & Linke (1989), all described deep, 50 m to >400 m, buried channels of the Elsterian in north-western Germany. They all regard the origin of the valleys as the result of subglacial processes. The upper part of the infill consists mainly of fine silty sand and olive-grey to grey-black clay, (The Lauenburger Ton, Hinsch, 1979), and fine sand, clay and diamictons (Ehlers & Linke 1989). The lower infill consists mainly of sequences of coarse and fine sand with gravel and clayey, laminated sand. Tills are relatively rare in the channels (Hinsch, 1979) but Ehlers & Linke (1989) could follow characteristic till layers over distances of several kilometres. Piotrowski (1994a) described a tunnel valley as a polygenetic feature which initially formed by subglacial erosion during the Elsterian glaciation and which also acted as a drainage system during the subsequent glaciations.

4.2.3 The Netherlands

In the northern Netherlands Elsterian meltwater deposits occur in depressions varying in

depth between approx. 10 m and >100 m. They consist of hard, dark brown clay, fine, micaceous, locally laminated, sand and fine- to medium-grained aeolian sands.

In a pit near Peelo, the type locality of the Elsterian Peelo Formation (Zagwijn, 1973; Ruegg, 1975), typical Scandinavian gravel has been found at the top of the Elsterian deposits. In two boreholes, notably Den Burg (9B-36) and Tzum (6D-49) in Friesland, rhythmites of Elsterian age have been found. The Tzum borehole was drilled in a depression over 100 m deep. About 80 m of the infill consisted of stiff dark brown clay. At the base of the depression the infill is formed of fine sand. These deposits are partly comparable with the Swarte Bank Formation in the North Sea (Cameron et al., 1986). The Elsterian deposits in this borehole are overlain by marine Holsteinian deposits (Zagwijn & Van Staalduinen, 1975). The pollen content is of reworked Tertiary (mainly Miocene) origin. Locally at the edge of the valleys aeolian sand is found. The heavy mineral assemblage of fine sand intercalations in borehole 12D/93 between 40 m and 28.50 m near the type locality at Peelo is characterized by garnet, epidote and hornblende. The glauconite content is low (Zandstra, 1975). All deposits are referred to the Peelo Formation.

Ter Wee (1983a) describes the occurrence of channels up to 350 m deep in the northern Netherlands. Ter Wee assumed that an erosional process which acted from north to south formed the valleys. In his opinion the formation of such deep channels warranted the presence of a thick ice sheet during the Elsterian glaciation. This ice sheet should have deposited tills, but tills of this age are rare in the area. Furthermore meltwater originating from such an ice sheet should have led to deposition of fluvioglacial sediments containing abundant Scandinavian rocks. However the sediments Ter Wee found, as valley infill indicates a southern origin. This led Ter Wee to suggest that the channels belong to an older system. He even concluded that the Elsterian ice sheet did not reach the northern Netherlands at all, but halted to the north and east of the mainland.

Bosch (1990) describes in the northern Netherlands 20 km to 30 km long channels, 3 km to 5 km wide and locally up to 350 m deep. For the genesis of the channels he adopts the model of Wingfield (1990) (see 4.4). Measurements on sedimentary structures pointed to an infill from north to south (Bosch pers. comm., 1994).

4.2.4 Great Britain

Woodland (1970) described the buried tunnel valleys of East Anglia after mapping a complex system between 60 m and 100 m deep, narrow, steep-sided, of buried channels with irregularly undulating longitudinal profiles. He assumed that these valleys originated by subglacial erosion during the melting of the East-Anglian ice sheet. Cox (1985) investigated and mapped three such buried valleys and recognized different channeling events. The latter gave evidence to show that a subglacial mechanism is not required to explain the presence of buried valleys; apparently a pre-glacial drainage system had been developed in response to a low sealevel. He explained closed basins in the buried valleys as the result of overdeepening of a preexisting valley by subsequent ice action.

4.3 Offshore areas with Elsterian valleys

More recent work concerning offshore valleys has been published by Boyd et al. (1988) in which they describe similar valleys from the Scotian shelf off Eastern Canada. Here channels occur that are up to 450 m deep, 2 km to 3 km wide, and which have steep walls. They show variable depth along the channels and form an unusual interconnected network. The

channels were formed subglacially because their characteristics are unlike those of submarine canyons which deepen downslope or at least close to the shelf break. The depth of the channels, the network pattern and the along-channel gradients do not equate with a fluvial origin. Sea-level stands during the Pleistocene were never more than approximately 200 m below present day level. This precludes incision of channels with an axial depth of over 400 m below the present sea-level (Boyd et al., 1988).

On seismic profiles from the Danish sector of the North Sea four generations of buried erosional valley systems have been observed. The valleys are between 0.5 km to 3.5 km wide and vary in depth between 120 m and 210 m below the sea bed. Biostratigraphical correlation between five boreholes, based on both the foraminiferal content (Jensen, 1991; 1992) and amino acid analysis (Sejrup & Knudsen, 1993) suggest that the oldest valleys were eroded during the Saalian glaciation. As a possible reason for the lack of Elsterian valleys the authors suggest that the ice sheet was non-erosive in this area, or more probably glacial sediments were deposited and subsequently eroded during the Saalian glaciation (Salomonsen & Jensen, 1994).

The valleys in the Dutch sector of the North Sea are eroded into the fluvial and deltaic sediments of the Yarmouth Roads Formation which mainly consist of sand locally with clay layers. In northern Germany, however, the valleys have also been eroded into Tertiary (Miocene) clay. There is no significant difference in the geometry of the valleys from those in the North Sea. This suggests that the geometry is independent of the lithology of the pre-Elsterian substrate (De Groot, et al., 1993). Accordingly it may be assumed that the process of formation was that of a very high energy environment.

The deep valleys have an irregular base along their longitudinal profile, as observed in Denmark by Ussing (1904). The most important process during the incision of the valleys must have been subglacial piping according to Boulton & Hindmarsh, (1987), Ehlers & Linke (1989), Ehlers, (1990), and Piotrowski, (1994a).

4.4 Models for the origin of valleys

Boulton & Hindmarsh (1987) (Fig. 20) demonstrated a model for the development of deep valleys in which meltwater from tunnels beneath a temperate ice sheet removes the sediments by forming channels which subsequently are filled with ice. In this model the terminal zone of the ice sheet, where the aggregate discharge and the hydraulic gradients will be at their highest, the produced water pressure values will equal the overburden pressures. This process may produce subglacial 'pipes' at the glacier terminus and also growth of sediment-floored subglacial tunnel valleys. Enlargement by the ice sheet results in increased subglacial drainage and the channels need to sustain ever larger discharges to maintain stability at the glacier sole. As a result the meltwater stream underneath the ice 'pumps' the sediment towards the proglacial zone.

Praeg (1993) interpreted seismic profiles from the southern North Sea which cross the valleys and include a line made by the RGD in a north/south isolated valley in the eastern K-blocks. He concluded that the internal reflectors in most channels are dominated by events expressed in axially downlapping reflectors in the longitudinal profile. The downlapping reflectors represent unconformities grading into conformity which define broad channel surfaces dipping at 5° in a northern direction. He concludes that the internal events reflect a

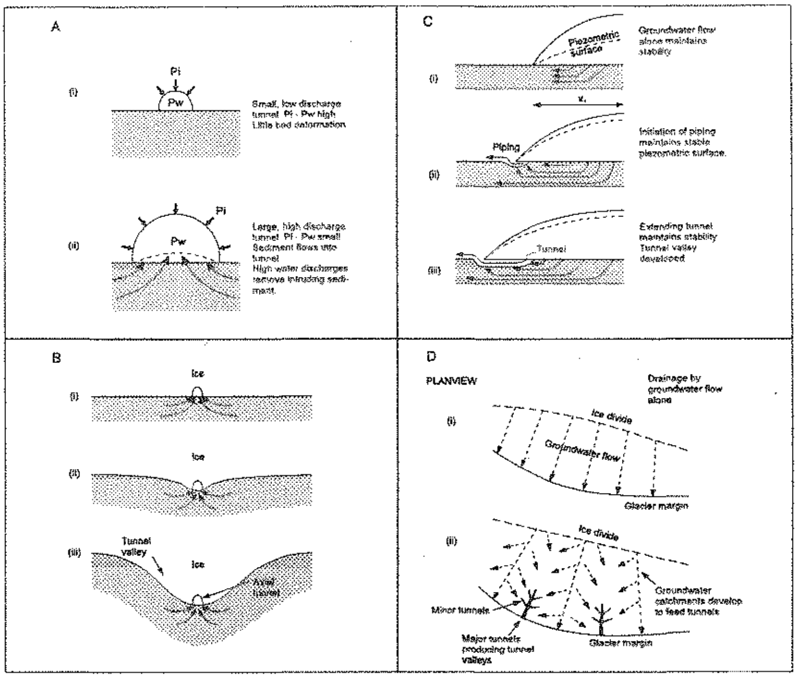


Fig. 20. The suggested process of the formation of tunnel valleys (after Boulton & Hindmarsh, 1987)

periodic erosion and deposition from south to north during the progressive channel fill. According to Praeg the upper part of the infill with glaciolacustrine clay took place after the melting of ice in an ice marginal lake.

The hydraulic pressure underneath the ice must have been too high for backfill processes as proposed by Praeg and the sediments which were derived by creep and fluviatile transport (Boulton & Hindmarsh, 1987) flowed 'uphill' along the axis towards the margin of the ice sheet progressively filling up the basins from north to south. The dip of the reflectors point to a low angle of only 5° a figure also given by Praeg (1993).

Van Dijke & Veldkamp (1995) proposed that the formation of subglacial valleys took place during the retreat of the Elsterian ice sheet. The authors interpret the development of tunnel valleys during the Elsterian glaciation as the result of relatively rapid and continuing increase in ice sheet margin temperatures thus causing an increase of meltwater. The high meltwater production during deglaciation maintains a progressive retreat and prevents the tunnel valleys from reaching stable groundwater flow conditions. The assumption of a progressively retreating ice margin is supported by the fact that the valleys are rarely found to be disturbed by large glaciotectonic features. This could also explain the relatively close spacing and narrow appearance of most of the valleys. According to these authors phases of rapid retreat alternated with periods of slowing down of retreat. If the meltwater production is related to changing mean summer temperatures, the production would have been much lower during a slow retreat. This mechanism could account for the formation of thresholds at the base of the valleys marking a more stable ice sheet position during phases of low retreat.

The process as proposed by Van Dijke & Veldkamp could explain the clay-rich material of the second and third phase of infilling (see below). During the retreat proglacial lakes were formed in which the finer-grained deposits were laid down.

Wingfield (1990) has proposed a new model for the formation of major valleys in the North Sea. He studied valley systems from the Late Weichselian (see Chapter 7), with valleys up to 5 km wide, 25 km long and 100 m to 350 m deep in the area north of the Dogger Bank. He believes that the major incisions are the product of a single mechanism i.e. the outburst of intra-ice sheet lakes (several tens of km^3) forming jökulhlaup plunge pools along the margins of an ice sheet. The resulting catastrophic meltwater discharge at the margin of an ice sheet scours the subsurface and creates the incisions. The drainage will take place in an extraordinaryly short period of time-as little as 3 hours with a peak outflow of 1 km^3/8s. at a velocity of 50 ms^{-1}. Wingfield refers to known lakes with a water volume of 0.01 to 4 km^3 . This hypothesis has given rise to much discussion (Hamblin et al., 1991). The consequence of the jökulhlaup model of Wingfield is that the southern North Sea must have been dry. Such deep erosion by fluvial processes during outbursts of intra-glacial lakes could not take place when there was an ice marginal lake because this would have diminished the erosional power of the floodwater (Hamblin, 1991). Van der Meer (1990) draws attention to the steep walls of the valleys. In areas with sandy sediments there must have been a force acting which prevented the walls from slumping. He also disagrees with Wingfield about the size of the intra-glacial lakes, pointing out that no similar lakes are known from present-day ice sheets. Van der Meer is of the opinion that to create such a lake the melting of the ice sheet must be very local and this is only observed in areas where volcanism exists beneath the ice sheet (Van der Meer & Vis, 1986; Sugden & John, 1976). In none of the glaciated areas with deep depressions were volcanos known to be active. Even the most well known present-day example in Iceland, the Grimsvotn caldera underneath Vatnajökull, does not produce enough water to create comparable deep depressions. Thorarinsson (1953) explains that in this ideal situation it takes ten years to create a glacial lake with a maximum water volume of 7,5 km^3. Nevertheless Van der Meer (1990) agrees that, although there are no recent examples in glaciated areas of the processes assumed by Wingfield, deep valleys may have been formed occasionally in Northern Europe by outbursts of intra-glacial lakes.

The presence of fresh water lakes beneath the base of 3700 metres of Antarctic ice however has been proved by British and Russian scientists. Underneath the Russian Vostok station an enormous lake of some 10,000 km^2 and 500 metres deep is present due to geothermal heating of the ice (Kapitsa, 1994). Although the temperature of this lake is below zero, the enormous pressure due to the thickness of ice prevents the water from freezing. As soon as the water is relieved of this pressure or the thickness of the ice lessens so that the heat is transferred to the atmosphere the water will freeze (Van der Meer and Van der Wateren, pers. comm.).

4.5 Glaciolacustrine and glaciomarine deposits (Swarte Bank Formation)

4.5.1 Seismic interpretations

Most of the seismic profiles in the K-blocks of the Dutch sector and which are used for the present study of the Elsterian valleys were surveyed with a nine-element EG&G sparker and a single element receiver array. The data are stored digitally, but because it was collected with single channel equipment, this has prevented processing. Because of this the seismic interpre-

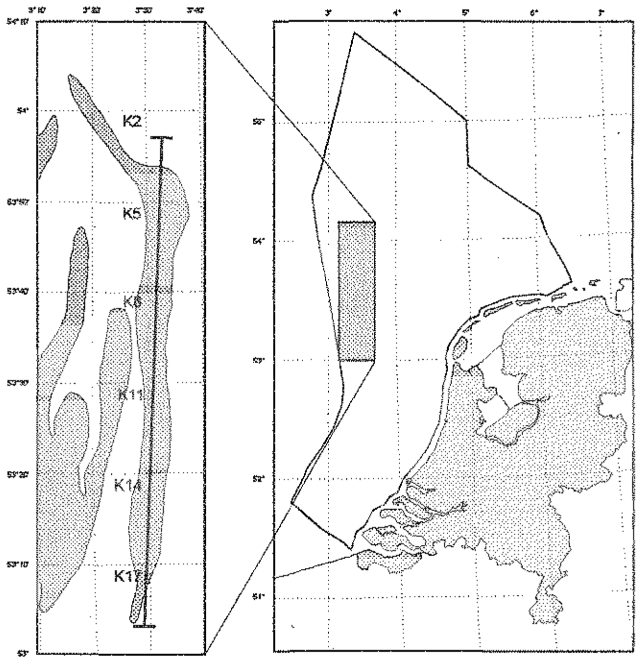


Fig. 21. Position of the seismic profile run along the K blocks valley. Block numbers are shown.

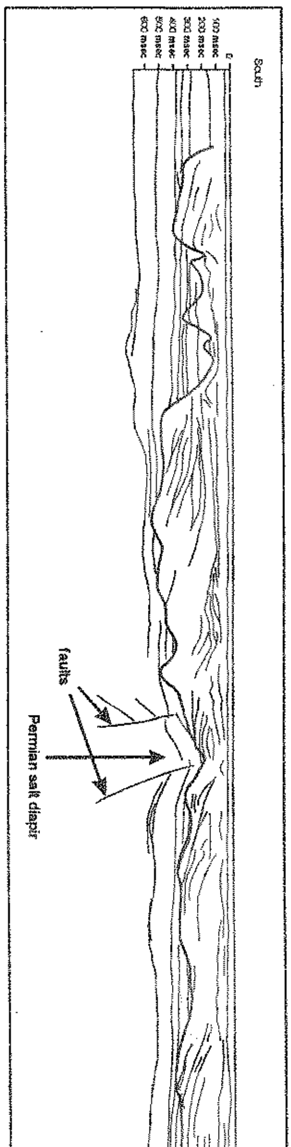


Fig. 22. Interpretation of the seismic profile of Fig. 21 with basin thresholds.

tation of the infill has mainly been done on profiles from the British sector (Cameron et al., 1986) and also on a recently completed seismic survey in the K-blocks. In blocks north and north-east of the K-blocks a number of recently recorded and processed multi-channel seismic lines are available but unfortunately only a few Elsterian valleys are present in these blocks.

Three phases of infill can be distinguished from the seismic profiles. The basal infill is structureless or has a chaotic reflector configuration. This part of the infill probably comprises gravelly, coarse sand, and possibly occasional till layers which are deposited penecontemporaneously with the incision of the valleys. In the southern part of the area this facies has completely infilled the shallower valleys.
In 1994 a multichannel seismic line was run along the centre of an isolated north-south trending valley in the western K-blocks. The line starts in the south of block K17 then runs through blocks K17, K14, K11, K8, K5 to K2 (Fig. 21). The line has been processed and approx. the upper 600 metres have been interpreted and digitised (Fig. 22). The water depth increases from 29 m in block K17 at the

southern end to 45 m at the northern end of the line. The southern end of the valley terminates abruptly and the bottom reflector dips steeply between about 270 m and 90 m below the sea bed. At the northern end the valley ends less abruptly. The longitudinal profile of the valley shows a succession of depressions which are cut into pre-Elsterian formations. The minimum and maximum depths of the valley are 160 m and 495 m respectively, the average being about 330 m. The difference of altitude of the thresholds between the basins range between about 270 m and 90 m. In the centre of the valley the top of a salt dome has been eroded. The reflections show no indications of strong upward movement of the salt since the Elsterian glaciation. Most of the depressions show northward dipping prograding reflectors which locally reach almost to the upper part of the valley infill. Apparently they represent a major depositional episode. At the top horizontal and gently inclined reflectors indicating the second and third phases of infill are present. In the centre of the valley, and in the upper infill, a valley up to 90 m deep has been eroded. It is not clear if this channel is Elsterian or post-Elsterian. The top of the third phase of infill occurs at a depth of between about 108 m and 60 m below the sea bed.

The downlapping reflectors of the first phase of infill in all the depressions in the valleys are identical and must be regarded as the result of the same processes. The dip of the reflectors point to a low angle of deposition of only 5°.
During the second phase of infill the seismic profiles of most of the valleys show a sub-parallel layering which has been draped over topographic irregularities on the surface of the underlying sediments.

The valleys on the Scotian shelf also have a chaotic basal infill on the seismic profiles. In boreholes the infill consists of stiff olive-grey structureless silty clay with only a little bioturbation (Boyd, et al., 1988).

4.5.2 Borehole data

The valley infills are mainly interpreted from seismic profiles because the maximum depth of shallow boreholes drilled in the valleys is 100 m or even less below sea bed. A selection of these shallow boreholes are described below to implement the upper part of the seismic profile and provide firm geological data. The boreholes are selected across valleys on a more or less east/west cross line.

Boreholes (Fig. 23) indicate that the infill of the second phase mainly consists of glaciolacustrine/glaciomarine clays including silt, silty clay and very fine to fine-grained sands. The third phase of infill is present above an erosional surface which has been cut into the parallel-bedded sediments in some of the valleys in the eastern part of the area. The unit of the third phase mainly attains thicknesses of up to 30 m. The seismic profiles suggest this unit may comprise a Late Elsterian delta-related influx of fine-grained sands and clays (Cameron et al., 1986, 1989). The sediments of the infill of the valleys are referred to the Swarte Bank Formation (Late Elsterian to Early Holsteinian).

Block K7

In borehole K7-7 between 77.10 m and 59.60 m below MSL an alternation of sand, clayey very hard silt and very silty, very dense fine-grained sand without marine indicators is present which probably belongs to the third phase of infill. The overlying marine sediments were de-

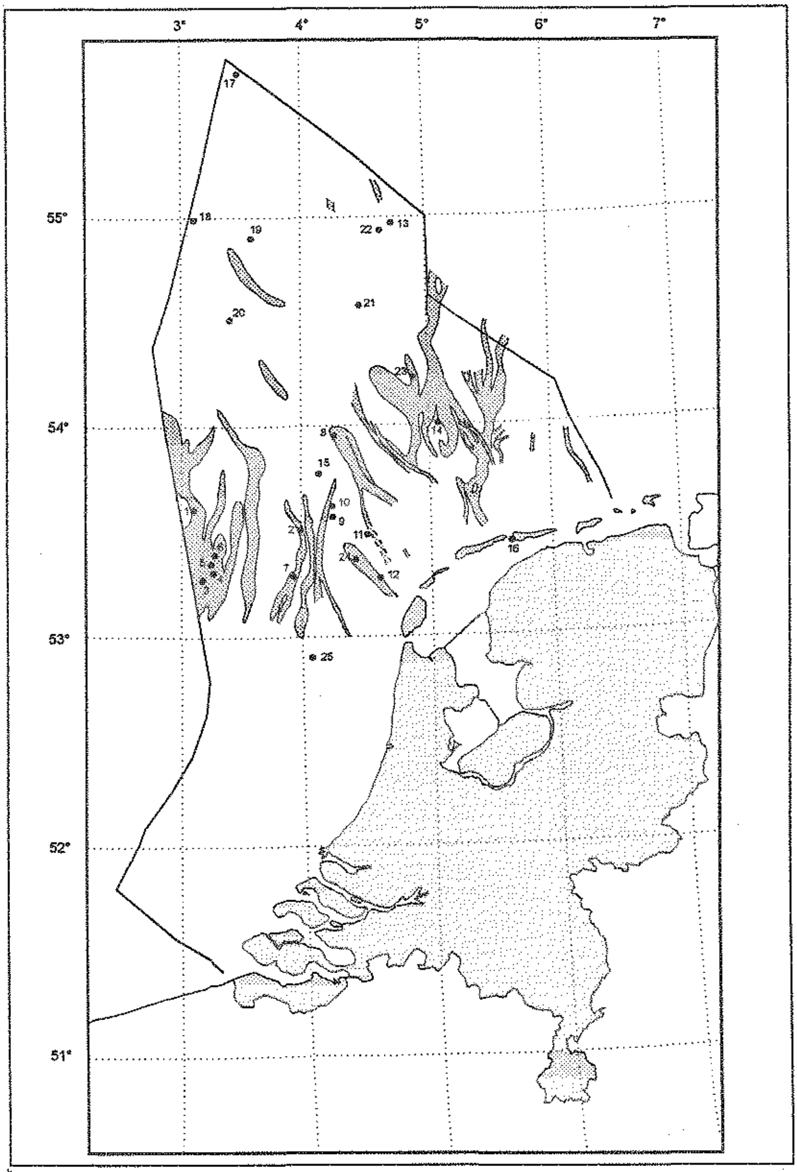


Fig. 23.
Map showing position of the Elsterian valleys together with borehole locations mentioned in the text.

1 = K7 - 4
2 = K12 - 29
3 = K13 - 5
4 = K13 - 6
5 = K13 - 7
6 = K13 - 8
7 = K15 - 9
8 = L1 - 4
9 = L7 - 10
10 = L7 - 11
11 = L14 - 66
12 = L11 - 7
13 = F3 - 45
14 = G16 - 22
15 = L4 - 21
16 = M11 - 39
17 = A5 - 9
18 = E1 - 10
19 = E2 - 3
20 = E8 - 4
21 = F8 - 6
22 = F2 - 6
23 = F15 - 30
24 = L11 - 71
25 = Q1 - 24

posited during the Holsteinian, Eemian and Holocene transgressions respectively. Between the Holsteinian marine sediments (referred to the Egmond Ground Formation) and Eemian marine sediments (referred to the Eem Formation), glaciolacustrine clay of the Saalian glaciation, which is referred to the Cleaver Bank Formation, is interbedded. The borehole has been drilled in a shallow part (less than 100 m below sea bed), of a north-south valley which is only faintly visible on the seismic (unprocessed sparker) profile. North and south of the borehole position the base of the valley is much deeper and is clearly visible on the seismic profile.

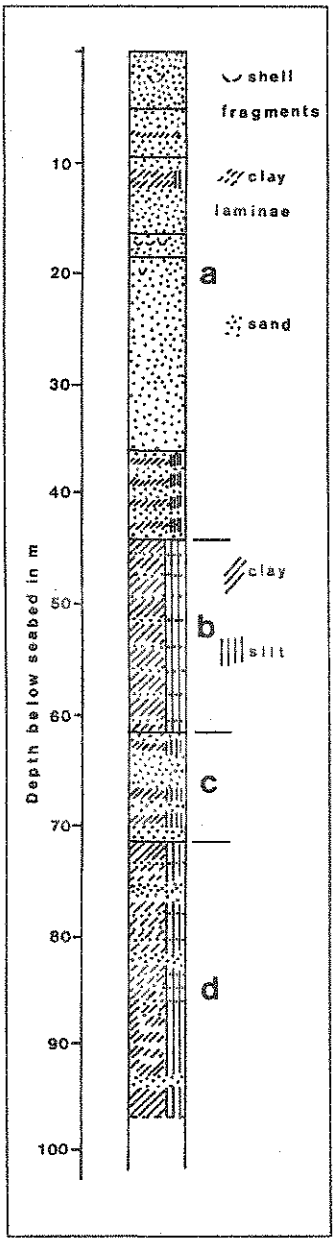


Fig. 24. Lithological profile of borehole K12-29. Water depth 28.00 m (MSL).
a = Holsteinian, Eemian and Holocene marine deposits
b = Third phase of infill
c = Sandy layer
d = Second phase of infill

Block K12

Borehole K12-29 has been drilled in the central part of a 360 m deep valley (Fig. 24). The infill, between 124.90 m and 100.50 m below MSL, consists of silty, stiff to very stiff, dark grey, laminated clay (5Y4/1). Between 100.50 m and 89.30 m grey (5Y5/1) slightly silty, fine sand with laminated clay layers occurs. From 89.30 m to 72 m the infill consists of very silty, stiff to very stiff, dark grey thinly laminated clay (5Y4/1) and was probably deposited during the third phase of infill. Foraminiferal analyses on samples between 123 m and 73.70 m below MSL revealed a poor fauna with at the base a mixture of arctic and boreal species including *Elphidium excavatum f. clavata, Nonion orbiculare, Elphidium excavatum f. selseyense* and *Ammonia beccarii* (Van Leeuwen, 1995). This probably indicates marine reworking during the Holsteinian transgression.

On the seismic profile the shoulders of the valley are not clearly visible. At 158 m a horizontal reflector occurs probably representing the base of the second phase of infill. At about 73 m below MSL a horizontal reflector is present dipping slightly towards the centre of the valley and probably represents the top of the second phase. The sandy unit between 72.50 m and 61.30 m recorded in the borehole is not visible on the seismic profile.

Block K13

In this block four well-cored boreholes have been drilled in a more or less north-east/south-west line through a complex valley system. Two seismic profiles cross the system in a north-east/south-west and a north-west/south-east line. On the seismic profile four valleys, initially separated, are present which become connected with each other during a later phase. At the base of the four valleys hardly any reflectors are present. However above their base a sequence of horizontal and subhorizontal reflectors occur continuously. The reflectors tend to dip slightly towards the north. The westernmost valley reaches to 400 m and the more eastern valleys to 350 m, 330 m and 225 m respectively below sea bed (water depth approx. 25 m).

Borehole K13-5 was drilled on the western margin of a valley which reaches to 427 m below MSL. The borehole is some distance to the south of the seismic line. Underlying Holsteinian marine, Eemian marine, Weichselian periglacial and Holocene marine sediments, the infill, between 113.80 m and 96.30 m below MSL, consists of stiff to very

stiff silty to slightly sandy clay with many thin sand layers. Between 96.30 m and 93.30 m a bed of fine sand is present. Between 93.30 m and 82.30 m the lithology is similar to that between 113.80 m and 96.30 m. At 113.80 m sediments of the Yarmouth Roads Formation were encountered consisting of fine- to medium-grained sand with gravel and shell fragments. Foraminiferal analyses indicated (between 110.55 m and 107.90 m below MSL) a transition from an arctic marine environment of deposition with species like *Elphidium excavatum f. clavata* and *Nonion orbiculare* to a boreal environment in which species like *Elphidium excavatum f. selseyense* are dominant and *Elphidium excavatum f. clavata* decreases (Van Leeuwen, 1995). This probably indicates a gradual transition from Elsterian arctic marine to Holsteinian boreal conditions. This is in contrast with the earlier view that there was a hiatus in sedimentation between the end of the Elsterian glaciation and the Holsteinian transgression (Cameron et al., 1986). A gradual transition from arctic marine to boreal marine conditions has also been described in Schleswig-Holstein by Woszidlo, (1962) and Lange, (1962) based on foraminifera and ostracods. Menke, (1968; 1970) concluded that based on pollen analyses the marine transgression was locally noticeable during the melting of the Elsterian ice sheet. The Holsteinian sea transgressed directly into the Elsterian glacial basins according to Menke, (1968).

The Early Holsteinian clayey sediments are referred to the Swarte Bank Formation.

Borehole K13-6 was drilled north-east of borehole K13-5 in the centre of the third valley and just south of the seismic line. In this borehole the top of the third phase of the valley infill was reached at 107.05 m below MSL. The sediments consist (between 112.15 m and 107.05 m below MSL) of fine very silty, slightly clayey sand (5Y3.5/2). At the base of these sediments a strong reflector occurs which probably represents the top of the second phase of infill. The second phase of infill occurs between 118.85 m and 112.15 m and consists of an alternation of fine sand and clay. Between the base of the borehole at 129.35 m and 118.85 m a very stiff to hard clay (2.5Y3/0) with laminae of fine sand has been sampled. The borehole did not penetrate the base of the valley.

Borehole K13-7 was drilled just north of borehole K13-6 and lay on the line of the seismic track. Between 121.20 m and 98.70 m below MSL the infill consists of an alternation of layers of very silty, fine sand and clay (5Y3.5/2). Between 125 m and 121.20 m below MSL a layer of silty, dark grey sand is present overlying a slightly sandy, hard, very dark grey clay (2.5Y 3/0) with sand laminae which extended to the base of the borehole at 128.70 m below MSL. The sediments below the sandy layer probably belong to the upper part of the second phase of infill. This borehole did not penetrate the base of the valley.

Borehole K13-8 was drilled just north of the seismic line on the western margin of the valley. Between 110.60 m and 89.30 m below MSL an alternation of sand, silt and clay layers (5Y4/1) overlies a very silty, sandy, stiff to very stiff, dark grey clay (5Y4/1) with sand and silt layers. The sediments probably belong to the third phase of the infill. At 117.50 m the borehole just penetrates marine deltaic sand deposits of the Yarmouth Roads Formation.

Block K15

The borehole in this block was sited on the eastern margin of a narrow <100 m deep north-north-west/south-south-east trending valley. At about four nautical miles north of the borehole the valley deepens to 300 m. In borehole K15-9 and below Holsteinian marine, Eemian

marine, Weichselian periglacial and Holocene marine sediments, deposits of the third phase of infill were encountered between 97.55 m and 95.55 m below MSL. The sediments consist of stiff clay, underlain by a layer of fine, slightly silty, very dense, grey sand (5Y5/1) between 101.35 m and 97.55 m. The second phase of infill is present between 110.05 m and 101.05 m and consists of silty, very clayey, dense sand and very stiff, grey clay (5Y4/1). At 110.05 m fluviatile sandy sediments of the Yarmouth Roads Formation were encountered.

Block L1

In borehole L1-4 drilled on the northern margin of a north-west/south-east trending valley, and below Holsteinian, Eemian and Holocene marine deposits very silty, slightly sandy, very stiff, dark grey clay (5Y4/1) is present between the base of the borehole at 102.15 m and 83.65 m below MSL. The clay is laminated with clay and silt and contains two thin beds, 1.80 m and 1.40 m thick respectively, of fine, very dense sand. The sediments probably belong to the third phase of infill. The base of the valley was not penetrated.

Block L2

Borehole L2-19 is located in a relative small north-west/south-east trending valley. Underneath a sequence of Holsteinian marine, Saalian glaciolacustrine, Eemian marine and Holocene marine sediments a silty very stiff to hard clay (5Y3/1) is present with seams of fine sand and silt between the end of the borehole at 140.50 m and 117 m below MSL. This borehole did not penetrate either the base of the valley. Sediments of the third phase of infill were not present. Pollen analyses which were carried out on borehole L2-1 at almost the same location revealed a high content of Tertiary pollen (Miocene and Pliocene) derived from sediments eroded by the ice sheet in the Baltic Sea and Denmark (Zagwijn, 1970a). The sediments in borehole L2-1 consist of very fine, silty sand and sandy clay with ice-rafted debris (dropstones) and shell fragments probably indicating a glaciomarine environment of deposition.

Block L11

Borehole L11-7 is located on the eastern margin of another north-west/south-east trending valley. Below Holsteinian marine, Saalian glaciolacustrine and Holocene marine deposits very hard, silty clay is present between the base of the borehole at 103.90 m and 67.60 m below MSL. Thin sand and silt laminae are present as well as thicker intercalations of fine to medium, dense to very dense sand which include many thin clay laminae. The sediments probably belong to the third phase of infill. The bottom of the valley has not been penetrated. At the north-western margin of the same valley borehole L11-71 was drilled. In this borehole marine clay is present between the base of the borehole at 52 m and 32.10 m below MSL. This clay is regarded as an Eemian infill of a Saalian valley and overlies the Cleaver Bank Formation which also consists of stiff, silty, very sandy clay locally containing ice-rafted debris. The base of the clay, forming the Cleaver Bank Formation, is at 69.20 m below MSL and overlies the Swarte Bank Formation. The latter formation in this borehole consists of alternations of clay and sand, laminated silt and fine, clay laminated sand to the base of the borehole at 120.50 m below MSL. In this borehole the first phase of infill appears to have been encountered.

Block F15

Borehole F15-30 is located in a small valley which is filled with dark grey, hard, very silty clay, laminated with fine sand (between 106.80 m and 78.80 m). At 106.80 m the Yarmouth Roads Formation was penetrated below the base of the valley.
Foraminiferal analyses carried out on samples between 98.60 m and 82.50 m below MSL revealed an arctic fauna with dominating species like *Elphidium excavatum f. clavata, Elphidium ustulatum* and *Nonion orbiculare* (Van Leeuwen, 1995), indicating glaciomarine deposition.
Fig. 25 shows a north-west profile through blocks G16 and F18 with up to 300 m deep Elsterian valleys in which the three phases of infill are recorded.

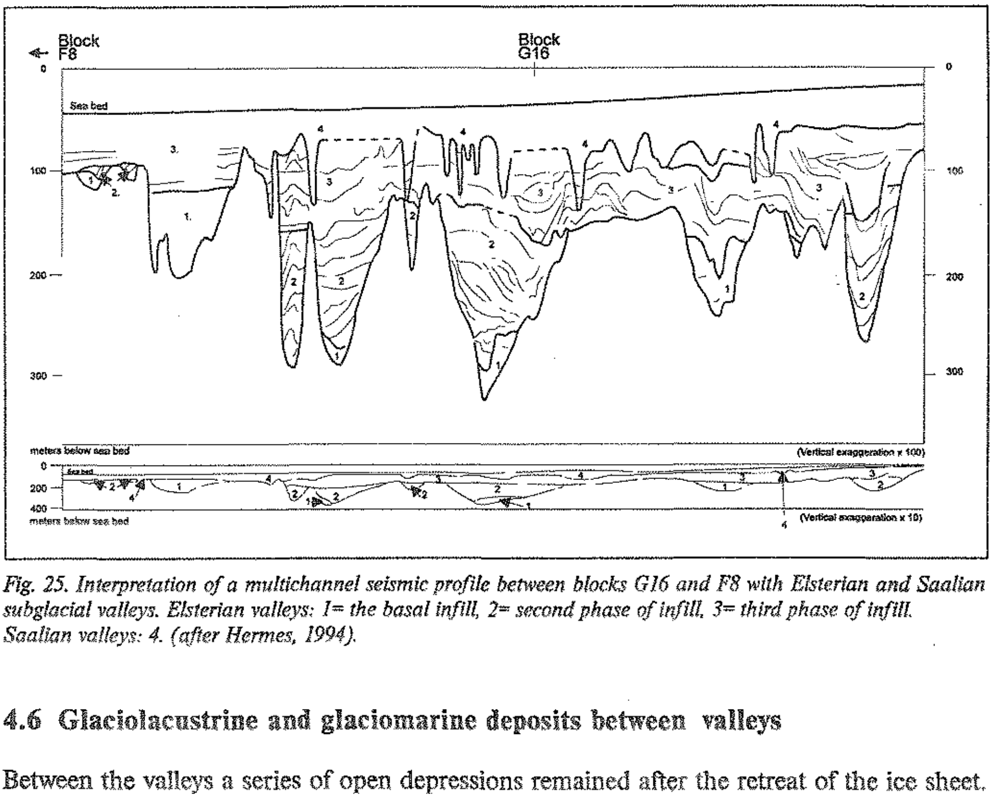


Fig. 25. Interpretation of a multichannel seismic profile between blocks G16 and F8 with Elsterian and Saalian subglacial valleys. Elsterian valleys: 1= the basal infill, 2= second phase of infill, 3= third phase of infill. Saalian valleys: 4. (after Hermes, 1994).

4.6 Glaciolacustrine and glaciomarine deposits between valleys

Between the valleys a series of open depressions remained after the retreat of the ice sheet. Elsterian clays, silts and sands of the Swarte Bank Formation were sampled in several boreholes. In the north-eastern part their origin thought to be glaciomarine is based on the sedimentary characteristics and the foraminiferal, mollusc and pollen content. The presence of Hystrichosphaeridae in the pollen assemblage also point to marine conditions.

In borehole A5-9 between 103.73 m and 86.30 m below MSL a sequence of very stiff to hard clay (2.5YN5/) locally with some silt and a thin sand layer was sampled. The foraminiferal content indicates a marine depositional environment with an arctic to high arctic fauna containing species dominated by *Elphidium excavatum f. clavata* and to a lesser extent *Buccella frigida, Cassidulina reniforma* and *Nonion orbiculare* (Neele, 1990). The mollusc fauna is arctic marine and contains typical cold species such e.g. *Portlandia arctica* and *Yoldiella interme-*

dia. *Portlandia arctica* suggests a lower salinity due to admixture of meltwater (Pouwer, 1991b)

In borehole E1-10 between 93.30 m and 70.40 m below MSL a sequence of silty, very stiff clay with intercalations of fine slightly silty to very silty sand was sampled. The foraminiferal content indicates a marine arctic-boreal to boreal environment dominated by species such as *Elphidium excavatum f. clavata* and *Buccela frigida* (Neele, 1986a). The mollusc fauna consist of marine arctic to high arctic species such as *Portlandia arctica* from a sub-littoral to littoral environment. Locally intervals containing no molluscs are present. Near the base between 89.45 m and 89 m fresh water species are present (Sliggers & Meijer, 1987). The pollen content indicates a glacigenic influence of British provenance (De Jong, pers. comm.). The deposits are overlain by Saalian glaciolacustrine clay of the Cleaver Bank Formation and are underlain by marine interglacial sediments from Cromerian IV age (Zagwijn, pers. comm.). The possibility exists that the sediments were deposited during the Holsteinian Interglacial under arctic to boreal conditions. The pollen content, however, points to the presence of ice close to the area of deposition and this would exclude an interglacial deposition. In borehole E2-3 located east of E1-10 a very stiff dark grey clay with fine sand at the base, and underlying Saalian periglacial sediments, was sampled between 86.50 m and 78.50 m below MSL. Foraminiferal analysis of the fine sand between 86.80 m and 70.50 m point to marine arctic to arctic-boreal conditions with the dominant species *Elphidium excavatum f. clavata* and *Nonion orbiculare*. The pollen is Palaeozoic and Mesozoic indicating a British provenance (Zagwijn, 1970b).

In borehole E8-4, at a depth of between 81.50 m and 73 m below MSL, a deposit of fine sand with clay laminations (77.90 m to 73 m) and silty very stiff clay (81.50 m and 77.90 m was sampled. The foraminiferal content indicates a marine middle-arctic environment with a water depth of approx. 50 m. The rich fauna is dominated by *Elphidium excavatum f. clavata* and to a lesser extent by *Cassidulina reniforme, Onion orbiculare, Buccella frigida* and *Bulimina marginata* (Neele, 1986b). The sand contains marine mollusc species indicative of an arctic to boreal environment with sub-littoral conditions. The mollusc fauna is poor marine. 'Cold' species are absent at the base but towards the top species such as *Portlandia arctica, Palliolum tigerinum* and *Parvicardium minimum* are present suggesting cooler conditions. Near the top fresh water species such as *Pisidium* and *Sphaerium* occur (Sliggers & Meijer, 1987). The pollen content consists of reworked glacigenic material of British provenance, and include sub-arctic pollen (De Jong, pers. comm.). The sediments are overlain by Holsteinian marine sediments and underlain by marine deposits with sub-arctic pollen but without a glacigenic influence (De Jong, pers. comm.). Zagwijn (pers. comm.) suggests that the underlying sediments were deposited presumably during interstadial conditions. Probably these conditions also prevailed during the Elsterian before the glaciation.

In borehole F8-6, between 103.53 m and 96.50 m below MSL, a firm to very stiff silty clay (7.5YR6/4) was sampled containing some shell fragments at the base. The foraminiferal content is rich and is dominated by *Elphidium excavatum f. clavata* and *Nonion orbiculare* and represents a shallow marine arctic environment. The molluscs are represented by arctic species such as *Yoldiella intermedia, Portlandia arctica* and, in the lower part of the deposit, the high boreal species *Retusa umbilicata*. The species indicate a shallow marine environment without fluviatile influences. The presence of *Portlandia arctica* however probably indicates the inflow of fresh meltwater (Pouwer, 1991a). The marine conditions probably occurred during the retreat of the ice in the Late Elsterian.

In Denmark in boreholes near Inder Bjergum in south-west Jutland (Buch, 1955) and near Hostrup in North Jutland marine deposits containing arctic foraminiferal faunas are found; they were probably deposited during the Late Elsterian (Knudsen & Feyling-Hanssen, 1976; Knudsen, 1977; Knudsen, 1987). They are overlain by Holsteinian marine sediments.

A transition from glaciolacustrine into glaciomarine sediments has been sampled in borehole L7-10 which, between 287.45 m and 99.05 m below MSL, contains a very silty, very stiff to hard, grey clay with thin silt and sand layers. Foraminiferal analyses revealed a very poor fauna, between 98.95 m and 98.75 m below MSL, which is between 94.40 m and 88.75 m below MSL overlain by sediments containing a fauna deposited in arctic to boreal conditions with species like *Elphidium excavatum f. clavata, Elphidium excavatum f. selseyense, Cassidulina-reniforme* and *Ammonia beccarii* (Van Leeuwen, 1995). The foraminifera probably indicate the transition from Late Elsterian non-marine into marine arctic and Holsteinian marine boreal conditions. This deposit overlies grey, sandy, slightly clayey, very dense, silty sediments which are present down to the base of the borehole at 109.15 m below MSL and which probably belong to the sandy deposits between the second and third phases of infill. The deposits are overlain by marine sediments of the Holsteinian, Eemian and Holocene transgressions.

In borehole L7-11 north-west of borehole L7-10, a very silty, very stiff to hard, grey clay occurs between 92.75 m and 84.45 m below MSL. The clay contains thin silt and sand layers which become more frequent towards the base. Between 97.75 m and 92.75 m below MSL a layer of fine- to medium-grained very dense sand is present which overlies a sandy, slightly clayey silt layer down to 98.50 m; the clay content in this layer increases towards the top. The Yarmouth Roads Formation is probably encountered at a depth of 106.25 m below MSL.
Both boreholes were drilled close to the margin of a narrow valley. Because the shoulders of the valley are not clearly visible on the seismic profiles it is possible that the boreholes penetrated part of the valley margin.

Borehole L14-66 was drilled close to the margin of a small north-west/south-east trending valley. Between 82.70 m and 72.70 m below MSL silty, slightly sandy, hard, grey (10YR3/1) clay is present. Between 119.80 m and 82.70 m the Yarmouth Roads Formation was sampled and consisted of fine- to medium-grained, dense to very dense, grey, fluviatile sand (10YR 5/1) locally with thin clay layers.

In borehole F3-45 between 95.20 m and 82.90 m below MSL, a very stiff clay is present, underlying the Holsteinian Egmond Ground Formation and overlying fluviatile deposits of the Yarmouth Roads Formation. In borehole M11-39, between 48 m and 39 m below MSL, clayey silt is present which contains very fine sand (Fig. 26). The sand content decreases upwards. Grain size analyses revealed a clay/silt ratio of 62% at the base and 84% at the top. The deposit is overlain by Holsteinian marine sediments and underlain by the Yarmouth Roads Formation.

Other boreholes in which comparable glaciolacustrine deposits to those in borehole F3-45 have been sampled are: F2-6 (98.40 m to 91.20 m), F8-6 (103.53 m to 96.45 m), and L4-21 (93.60 m to 69.80 m).
The only borehole south of the 53°N in which similar glaciolacustrine deposits are found lies in block Q1 (Q1-24 between 67.30 m and 54 m).
Except for the sandy layer between the second and third phases of valley infill no fluviogla-

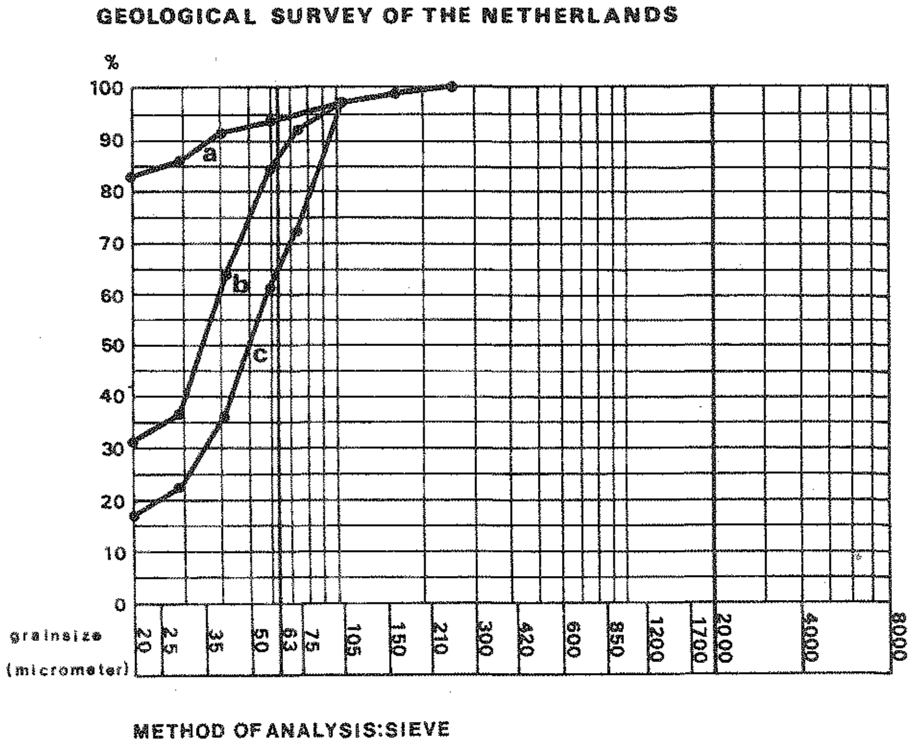


Fig. 26. Grain size analyses of three samples of the Swarte Bank Formation in borehole M11-39 (a, b, c).

cial deposits have yet been recognised. No formal name has been given yet to the Elsterian fluvioglacial deposits (Fig. 30).

In the German sector of the North Sea three boreholes have been drilled. In borehole BH89/3 Elsterian glacial, fluvioglacial or glaciomarine deposits were sampled between 91 m and 62 m below MSL. The deposits contain some Scandinavian gravel including flint, chert and crystalline material. There is a marked increase of gravel between 74.70 m and 62 m below MSL. The dark green-brownish, silty, and very fine, sandy sediments are laminated and have a similar lithology to the Lauenburger Clay. Deposition occurred in a glaciolimnic or glaciolacustrine environment. The lower unit is regarded as having been deposited during the Early Elsterian and the upper unit during the Late Elsterian. The deposits overlie Lower Pleistocene fluviatile sediments and are overlain by sandy deposits of Saalian age. In the other two boreholes comparable Elsterian deposits were sampled and can be similarly correlated. They are characterised by a high amount of reworked Pliocene and Lower Pleistocene sediments and contain up to 20% of 'fresh' Nordic (Scandinavian) gravel (Schwarz & Streif, 1991).

4.7 Till (Juisterriff Formation)

As mentioned above in the boreholes sunk in the valleys a number of them penetrated pre-Elsterian formations. No tills attributed to the Elsterian glaciation have been found except in

borehole G16-22 which according to the seismic profile was sunk in a narrow valley. The till here belongs to the Juisterriff Formation. In this borehole, between 109 m and 99 m below MSL, a calcareous, massive, dark olive-grey clay is present containing two sandy layers (101 m to 100.20 m and 103 m to 102.10 m). The upper and median clay layers are poorly sorted hard diamictons with a clay content of 12% (47% smectite and 37% illite) in a matrix-supported gravel composed of flint. The lower clay has a higher clay content and contains a few granules and gravel (Sha et al., 1991).
Thin sections have been made of two samples of the till Mi 625 (100.08 m to 100 m) and Mi 626 (104.28 m to 104.20 m). The till has been described by Van der Meer (1992) as forming part of a deformable bed characteristic of wet-based glaciers resting on a sedimentary bed. The till has a 'Scandinavian origin assemblage' with a noticeable amount of reworked Tertiary and older pollen (Zagwijn, 1991; De Jong, 1991). A second higher till present in this borehole between, 71.50 m and 67.05 m below MSL, also shows the same pollen assemblage. Van der Meer (1992) observed no lithological and microstructural differences between the two tills. Zagwijn (1991) and De Jong, (1991) assumed that both tills and the intervening marine sediments belong to the Saalian glaciation. According to Meijer, (1991) and Neele, (1991b) the sediments between the tills are thought to have been deposited in a tide-dominated glaciomarine environment. Sha et al., (1991) interpreted the lower till as Elsterian, the marine sediments as Holsteinian and the upper till to be Saalian. The present author agrees with Sha that only the upper till is Saalian in age (see Chapter 5 for further discussion).

North of the narrow valley described in blocks F18 and G16 another Elsterian valley has been interpreted from examination of high resolution seismic profiles in block G10. In the north-west and south-east corners of this block the valley is identified on two seismic lines and is thought to reach a depth of up to 83 m below MSL. The infill is Holsteinian and Eemian. The base of the valley is irregular. At its eastern margin Lower Pleistocene sediments occur at a very high level of only 8 m below sea bed. This valley probably forms the northern extension of the valley observed in the blocks F18 and G16.

The absence of Elsterian tills in the glaciated area of the Dutch and the British sectors (Cameron et al., 1984b; Balson & Jeffery, 1991) is probably due to erosion during successive transgressions of the Holsteinian and Eemian. Erosion of tills by younger ice sheets has only been possible in the north-western and north-eastern parts of the Dutch sector since there is no evidence for the presence of ice in the central part of the Dutch sector during Middle and Late Pleistocene glaciations. Another possible explanation for the apparent absence of tills is that their composition is more sandy which makes detection more difficult. Alternatively, tills may not have been deposited at all as a result of rapid outflow of ice and the formation of glaciotectonic basins from 53°N towards the southern limit of extent of the ice at 52° 20' N.

In the northern Netherlands Elsterian till has been found in only three boreholes. In borehole 5B-7 in the Waddenzee, Oostmeep, 0.30 m of till has been sampled at a depth of between 51.70 m and 51.40 m at the base of a depression and in a relatively small glacial valley. The gravel in this till is of eastern provenance only, with no Scandinavian rock fragments having been encountered. Pollen is Tertiary-Pliocene, Miocene or older (Van Staalduinen (ed.), 1977). In borehole Witmarsum (10B/191) in Friesland at a depth of between 226 m and 220 m a greyish-black, calcareous, very sandy till was sampled at about 20 m above the base of a glacial valley. The till is poor in coarser particles and consists of both fluviatile material of eastern provenance and a few fragments of Fennoscandinavian flint and granite (Zandstra, 1983b).

In another borehole on the former island of Wieringen (14E/110, Stroe II) two till layers occur. The deepest till is present between 60 m and 59 m at the base of a glaciolacustrine clay, the Peelo Formation. The upper till between 13.40 m and 1.20 m belongs to the Drente Formation (Saalian glaciation). Grain size analyses carried out on the lower Elsterian 'till' showed that the clay/silt percentage is 43 %, the D50 is 75.5 μm and the calcium carbonate content 7.2%. The gravel content is of eastern origin and derived from the fluviatile deposits of mid-German rivers. The flint, however is of typical Scandinavian origin (Zandstra, 1986).

In the during the Elsterian glaciated areas e.g. in Denmark three till units are found at several locations (Stephan et al., 1983; Sjörring, 1983, Houmark-Nielsen, 1987). In Britain, notably in Norfolk, several Elsterian tills are recognized including the Triassic till, the Lowestoft till and the North Sea Drift tills (Perrin et al., 1979; Boulton et al., 1984; Bowen et al., 1986; Eyles et al., 1989; Lunkka, 1988, 1994; Ehlers et al., 1991; Ehlers et al. 1992; Hart & Boulton, 1991). In northern Germany Elsterian tills occur which can be distinguished from Saalian tills by grain size, colour, $CaCO_3$ content and the high amount of pre-Quaternary sediments (Höfle, 1980; Ehlers & Linke 1989).
In the offshore area east of Great Yarmouth in Norfolk, Britain, geological investigations have been carried out by RGD for exploration of gravel in the "Norfolk" concession. The superficial gravel layer consists not only of a high percentage of flint and gravel of British provenance, but also Scandinavian gravel has been sampled but e.g. rhomb porphyry from the Oslo area in Norway, and granites from both Småland and Dalarne in Sweden (Zandstra, 1972a). This gravel is a reworked marine deposit. Divers observed at sea bed enormous boulders with diameters of more than a metre.

4.8 Deformation structures

Deformation of the sedimentary structures have been observed at several locations on seismic profiles south of 53°N, mainly near the Brown Bank. Moreover a very high level of Lower Pleistocene fluviatile sediments, relative to the sea bed and which is probably due to ice-pushing occurs locally in some boreholes (Oele, 1971; Cameron et al., 1984b). In one of the elevated areas borehole P3-25 was drilled. Below a cover of 9 m Eemian, Weichselian and Holocene deposits a bed of 1 m of very fine to fine, $CaCO_3$ free, sand has been sampled containing gravel (chert and crystalline) and some shell fragments (Spaink, 1982). These deposits are probably Lower Pleistocene and the gravel is possibly Elsterian outwash. The location however lies just west of the maximum limit of the Saalian ice sheet. A Saalian age suggested by Oele (1971) however cannot be excluded.

In the Brown Bank area a dense grid of east-west and north-south seismic lines was run and revealed deformation structures on both sides of the bank. These structures are also present close to the sea bed surface below the Brown Bank, but they are obscured on the seismic profiles due to of the thickness of the sand deposits forming the bank itself. The structures are attributed to shearing and thrusting of deltaic sand and clay deposits. High level Lower Pleistocene sediments were sampled in several boreholes including P4-8 at 8 m below sea bed (46.20 m -MSL), borehole P5-15 at 8 m below sea bed (50.60 m -MSL), and borehole P5-19 where at 7 m below sea bed (50.40 m -MSL) fine sand and laminated clay was sampled underlying Eemian, Weichselian and Holocene deposits. In borehole P8-7 under a cover of 1.79 m (41.79 m below MSL) of Holocene marine deposits, very fine, slightly silty, sandwith clay-laminae was sampled. Pollen analyses have shown that these sediments belong to the Early Pleistocene Yarmouth Roads Formation (Waalian) (Zagwijn, 1971a; Zagwijn, pers. comm.).

The top of the ice-pushed sediments forms a well-defined erosional surface. The top of ice-pushed sediments was probably originally much higher but has since been eroded.

Measurements of fold and thrust structures in seismic profiles have been carried out by Bammes (1986) at 22 locations on the east side of the Brown Bank. Table 3 indicates that there are two directions from which the deformation took place i.e. east and west. In this area Bammes recognises three distinct clusters (Fig. 27). In the northern and central clusters a western direction of push has been measured five times and an eastern four times. In the southern cluster an eastern direction of push is observed three times while in two cases the pressure came from the west. The push is the result of two ice lobes at each side of the present Brown Bank (Cameron et al., 1989) (Fig. 28).

The western and eastern margins of U-shaped valleys have locally been recognized on the seismic profiles. The complete valley lies below the maximum penetration of the shallow seismic system used. The locations of the deformation structures are shown in Table 3.

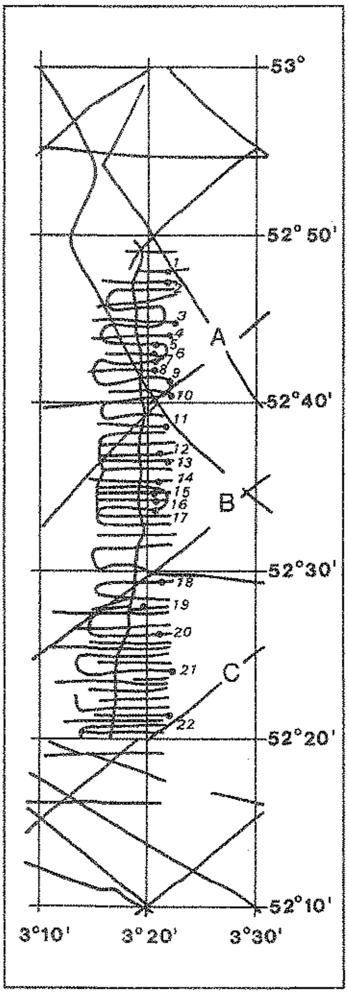


Fig. 27. Location of 22 measured deformation structures along the eastern side of the Brown Bank showing three clusters A= the northern, B= the central and C= the southern. The lines show the locations of the seismic profiles (after Bammes, 1986).

Coarse-grained, fluvioglacial sand with crystalline Scandinavian rock fragments has been sampled in borehole P7-7 (Zandstra, 1971a) (for the deposits no formal formation name has been given yet). The position of this borehole probably represents the southern limit of the

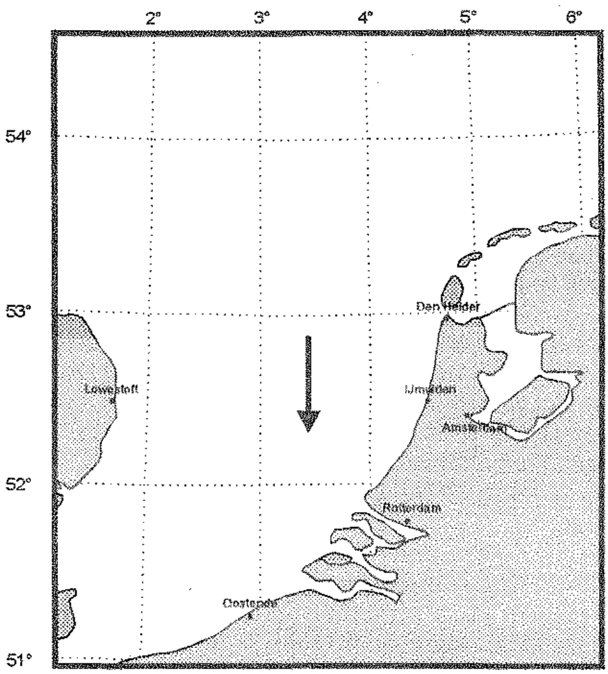
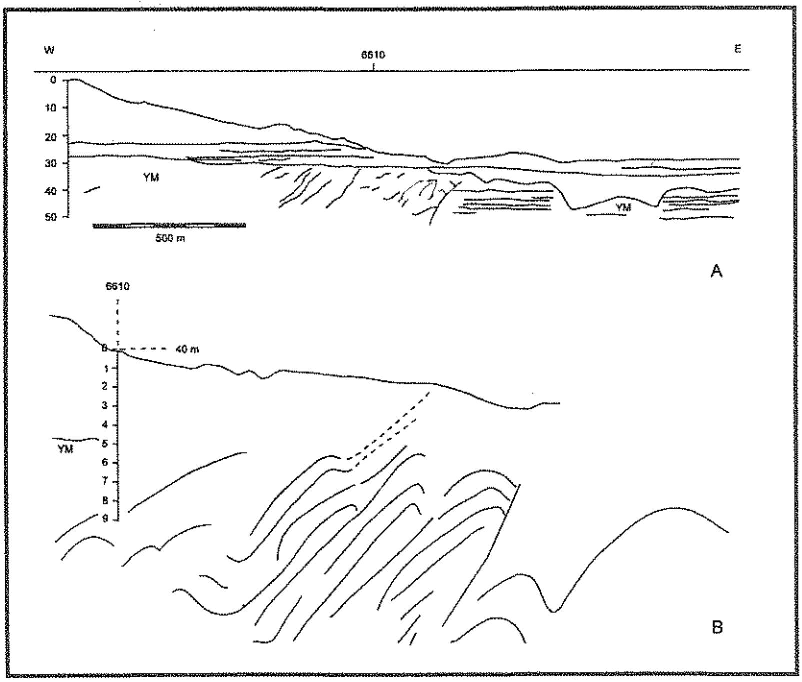


Fig. 28. (a) Interpretation of a high resolution seismic profile with folded and overthrust structures below the Brown Bank. (b) Interpretation of detail of the deformation structures.



eastern ice lobe. No data are available for the extension of the western ice lobe towards the south.

In borehole P5-4, north-west of the Brown Bank, the top of the Lower Pleistocene (Waalian) non-marine deposits (Toering, 1970) has been found at a depth of 37 m below sea bed (70.80 m below MSL). The deposits consist of 4.30 m of fine, laminated sand overlying a stiff laminated clay with a thickness of several metres. These are overlain by Cromerian(?) interglacial sediments which, according to the pollen analysis, are covered by deposits from a cold phase. In turn these are overlain by Holsteinian, Eemian and Late Eemian/Early Weichselian and Holocene sediments (Zagwijn, 1970c). The deposits near the Brown Bank must have been elevated by at least 24 m to 30 m.

It is not clear which glacial processes took place at the margin of the ice sheet at about 53°N. North of this latitude no deformation structures due to ice-pushing have been recognized on the seismic profiles and it is thought that mainly subglacial erosion took place. South of this latitude glacial basins were formed associated with deformation along the basins. The pre-Elsterian substrate was probably formed of fine, clay-laminated sand as sampled in many of the boreholes. Little is known however about subglacial conditions and the occurrence of permafrost.

4.9 Periglacial sediments (Middelrug Formation)

In the Dutch sector south of the maximum extension of the land ice, Elsterian periglacial sediments, which belong to the Middelrug Formation, have been recognized so far in three

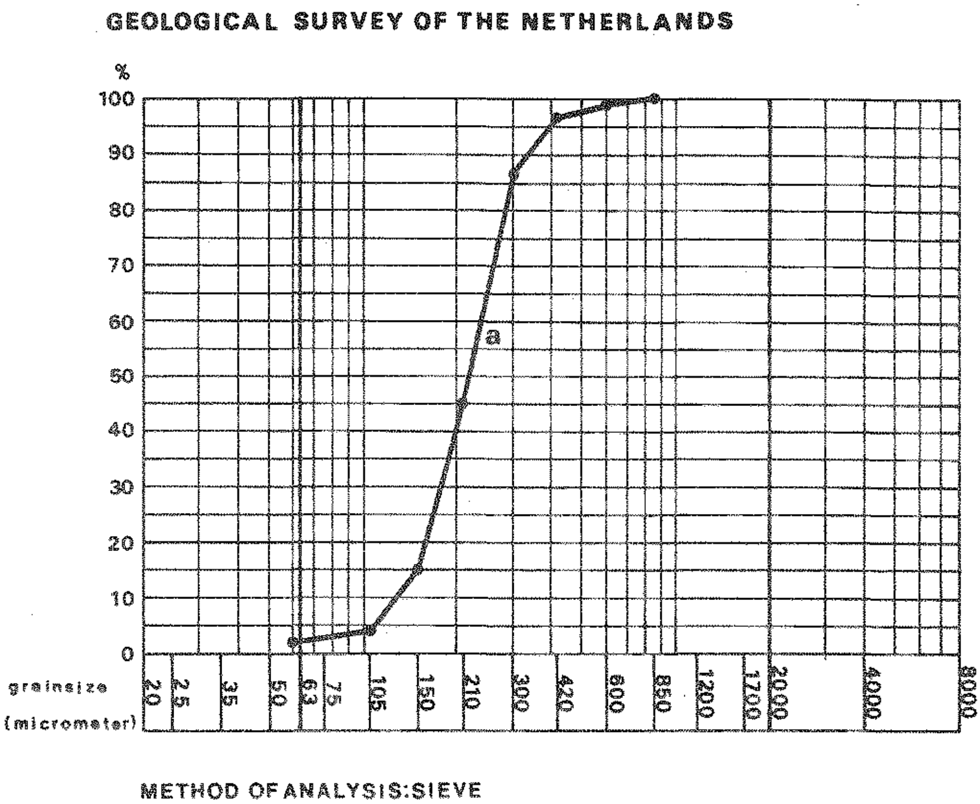


Fig. 29. Grain size analysis of the Middelrug Formation in borehole F3-2 (a).

boreholes. In borehole F3-2, the formation consisted between 79.30 m and 74.50 m below MSL, of yellow-grey fine sand with organic matter (Fig. 29). The deposit is underlain by the Yarmouth Roads Formation and overlain by the Egmond Ground Formation. In borehole Q5-209 the Middelrug Formation is formed of a layer of fine, dense, dark grey, micaceous sand, containing traces of peat and clay, and is present at a depth of between 51 m and 45 m below MSL and underlies Holsteinian marine deposits. The sand does not contain $CaCO_3$. The sand overlies the fluviatile Yarmouth Roads Formation. West of borehole Q5-209, in borehole P5-4 at a depth of between 66.30 m and 61.80 m, Middle Pleistocene interglacial (probably Cromerian) and Holsteinian marine deposits, consist of yellow-grey fine sand with silt laminae. The sediments are poor in pollen and indicate a cold phase (Zagwijn, 1970c). Because of their stratigraphic position and the absence of pollen and marine indicators, these sediments are regarded as Elsterian periglacial. Due to lack of sufficient data, the extent of periglacial sediments in the North Sea is not known. If they ever existed they may have been eroded during post-Elsterian glacial and interglacial stages (Cameron et al., 1993).

In boreholes in the Dutch Waddenzee aeolian sand deposits also occur along the margins of glacial valleys. They contain wind-polished gravel (Van Staalduinen (ed.), 1977).

4.10 Maximum extent of the Elsterian ice sheet in the southern North Sea

Woldstedt (1955) reconstructed the maximum Elsterian ice limit in the North Sea as running from the frontier between The Netherlands and Germany into the Ems estuary. From the mouth of the estuary the limit ran north-west into the North Sea north of the Dutch Frisian islands then towards the south-west to the Thames estuary. The northern Netherlands was free of ice during the Elsterian glaciation according to Woldstedt.

The reconstruction of the maximum extent of the ice sheet by the present author is based on study of the legacy left by glacial sediments and of landforms glaciated by the ice sheet. Within the maximum extent of the Elsterian ice in the Dutch sector of the North Sea, subglacial valleys, tongue-shaped basins with deformation structures along their margins are present. The maximum extent of ice during the Elsterian glaciation most probably ran from the Dutch coast at 52° 50' 00"N in a south-west direction towards Ipswich in East Anglia near the British east coast (Fig. 30).

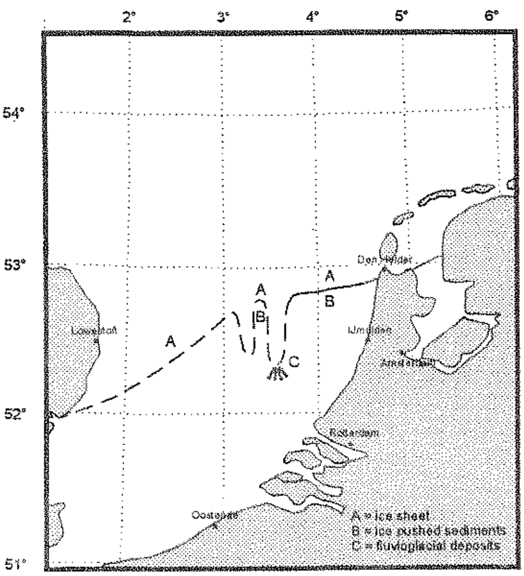


Fig. 30. The maximum extent of the Elsterian ice sheet showing the probable location of glacial tectonic basins and the position of fluvioglacial deposits.

4.11 Drainage history during the glacial maximum

Gibbard (1988) reconstructed the palaeogeography of the Elsterian (Anglian) Stage at its glacial maximum with an ice-dammed lake in front of the ice sheet, with drainage partly taking place over the Wealden-Artois anticline and over the north-western French coastal area. Gibbard and others (unpublished results) found sediments containing tills of waterlain origin and associated sand members in Norfolk which were deposited by ice advancing into a large waterbody. Gibbard (1988) suggests therefore widespread deposition in a glaciomarine environment in the southern North Sea. The sea-level was according to Valentine (1952) 90 m below present level and Fairbridge (1961) calculated a sea-level of about 48 m below present level.

Gibbard (1993) assumed that the existing complex system braided narrow channels in the Strait of Dover originated both by a combination of fluvial processes and tidal scour and probably dates from the Early Middle Pleistocene. During the Elsterian ice advance the lake between ice in the north and the Wealden-Artois anticline in the south became drained by overspilling through the Strait of Dover. This is supported by the occurrence of fluviatile sediments at Wissant in France (Roep et al., 1975). They distinguished three lithological units in the sediments the basal unit probably being deposited during a glaciation. Based on the type of sediment, their elevation and palaeocurrents the authors concluded also that the deposits date from the Saalian or an older glaciation. According to fossil mammal finds in the basal unit the deposits cannot be older than Elsterian Stage.

Praeg (1994) in his reconstruction projected a lake at least 100 m deep in the southern North Sea dammed by the Wealden-Artois anticline in the south and the ice-margin in the north. The buried channels should record contemporaneous erosion and backfilling of 'tunnel valleys' by subglacial to subaqueous meltwater drainage along an ice margin which was withdrawing to the north.

D'Olier (1994) identified a network of channel forms incised into the Tertiary London Clay, and offshore from north Essex and south Suffolk at approximately 52°N. He regards the 20 m to 900 m wide, up to 8 m deep below sea bed (20 m to 25 m below MSL), east-west channels as an Anglian ice-marginal drainage system. The infill is complex and consists of silty sandy tills which are Anglian and later in age, and which sometimes overlie poorly sorted sand and gravels.

The drainage history of meltwater rivers during the Elsterian glaciation is problematical. Until now, apart from the channel systems described above, no depositional evidence has been found to support the presence of a lake between the Wealden-Artois anticline in the south, and an ice sheet in the north. In the Dutch sector the glacigenic sediments must have settled on top of fluvial deltaic sediments and in the British sector on top of mainly Lower Pleistocene and Tertiary clay or clayey sand deposits.

The possibility exists that there was an overspill of water over the Wealden-Artois anticline. Woodland (1970) calculated that during the summer transport of sediment by subglacial streams in Western Greenland comprised 15,000 to 20,000 tons of clay and silt in suspension per day. This means that in a period of 2000 years up to 20,000 x 180 (=6 months) x 2000 = 72×10^8 ton will be transported. This is equivalent to an area of about 76 km^2 with a thickness of 45 m.

If it is assumed that during the Elsterian glaciation similar amounts of sediment became available, then it must have been deposited elsewhere. This leads to the conclusion that no single large lake existed and that meltwater deposits were transported directly south into the Atlantic Ocean. The present deeps in the southern part of the North Sea are probably the channels along which transport of the material took place. The channels are mainly cut into stiff Eocene clays and Cretaceous chalk. Post-Elsterian erosional processes further deepened the channels and at the same time removed Elsterian sediments.

4.12 Conclusions

From the considerable amount of information that has now accumulated both from the North Sea and surrounding land areas it is clear that the valley systems have been eroded during the Elsterian glaciation. The process of erosion has been mainly subglacial, especially piping, but other processes, although of lesser importance, like jökulhlaups and the use of preexisting fluvial valleys cannot be excluded (Russell, 1994).

During the advance of the ice south of approx. 53°N it appears that only shallow subglacial channels were formed.

Reinterpretation of sediments from boreholes sunk into the Elsterian subglacial valleys indicate that the second and third phases of infill are more complicated than initially thought from the seismic profiles. In the Dutch sector of the North Sea the Late Elsterian deposits of at least the third phase of infill are glaciomarine.

During the infill several processes must have played a role. The sediments of the first phase of the infill of the valleys have not been penetrated in boreholes. However some of the boreholes penetrated the upper part of the second phase sediments of the infill. These laminated sediments indicate deposition under low energy conditions during retreat of the ice sheet with the ice front situated relatively near the area of deposition. In several boreholes a sandy layer is present between the second and third phase of infill which indicates a phase of sedimentation under higher energy conditions. The sediments of the third phase of the infill were also deposited in a low energy environment in the southern and eastern part of the North Sea, possibly contemporaneously with the glaciolacustrine and glaciomarine sediments between the valleys. These deposits often contain reworked Pliocene and Miocene pollen which is of Scandinavian provenance. It cannot be excluded however that Tertiary sediments elevated by halokenesis, as for instance in the Dutch block K9 (Giesen & Mesdag, 1995), were locally eroded during the glaciation. In the British sector, the top of several salt domes occur close to the sea bed (Cameron et al., 1984c) and these have been have been reworked and transported by meltwater rivers. The glaciomarine clayey and sandy deposits contain mainly pollen of British provenance.

As demonstrated in borehole L11-71 during the Saalian glaciation Elsterian valleys were used again in some cases.

The absence of extensive till plateaux like those produced by the Saalian glaciation in the Dutch sector, is probably due to the type of glaciers which covered the area. It is possible that tills were deposited containing a high percentage of sand thus facilitating erosion and reworking during the post-Elsterian marine transgressions. The Holsteinian marine sediments are mainly fine-grained and generally contain no gravel. This is in contrast with the Eemian marine sediments in the North Sea which often contain Scandinavian gravel from Saalian deposits.

Only deformation structures and ridges together with the local occurrence of fluvioglacial sand and gravel south of the maximum extent of the ice sheet witness the presence of Elsterian ice in the area. In all probability ice streams with a high velocity moved southwards and formed tongue-shaped basins which resulted in deformation of the underlying fine sediments of the Yarmouth Roads Formation.
Stratigraphic evidence for syndepositional deformation during the Elsterian glaciation has not been found. The ice-pushed sediments are pre-Elsterian in age while the overlying sediments are post-Saalian. Although the ice-pushed deposits are Early Pleistocene in age (and pushing by Saalian ice cannot be excluded; see Chapter 5), it is more than likely that the area was covered by the Elsterian ice sheet.

There is no depositional evidence for the supposed lake between the ice-margin in the north and the Wealden-Artois anticline in the south proposed by several authors (Gibbard, 1988). Isostatic movements due to ice loading during the maximum extent of the Elsterian ice sheet, were possibly responsible for crustal downwarping of the Wealden-Artois anticline and as a result of which overspill may have taken place.

Chapter 5

The Saalian glaciation in the Dutch sector of the North Sea

5.1 Introduction

In the south-western and north-eastern parts of the Dutch sector of the North Sea a range of Saalian glacial and periglacial sediments and phenomena is found.
In The Netherlands all Saalian glacial sediments are placed in one lithostratigraphic unit, the Drente Formation (Zagwijn, 1961). The Drente Formation contains one till sheet, indicating a single ice advance. This contrasts with northern Germany where in certain areas three Saalian tills probably occur. These include the Drenthe Glacial Stage (Older Glaciation), the Middle Glaciation (Rehburger Stadial) and the Younger Glaciation (Warthe Stadial) (Duphorn & Kabel, 1980; Stephan et al., 1983; Grube et al., 1986; Ehlers, 1990). There are numerous publications on the Saalian glaciation in northern Germany, but unfortunately no formal lithostratigraphic units have been established in the Pleistocene sequence (Grube, 1981; Van der Wateren, 1992). This has led to a proliferation of different names by authors.

In Denmark three major ice advances are also recognized. The Norwegian Advance invaded Denmark from the north and according to Houmark-Nielsen (1987) reached at least as far south as the Danish-German border. The second ice advance, the Middle Saalian Advance, entered the country from a north-east direction and is correlated with the Drenthe Glacial Stage in Germany and The Netherlands. The third ice advance, the Paleobaltic Advance, invaded central Denmark from the east and east-south-east and extended into western Jutland (Houmark-Nielsen, 1987; Sjörring, 1983; Ehlers et al., 1984). In the central part of Denmark three different till units are recognised (Houmark-Nielsen, 1987).

The presence of a Saalian ice sheet in the southern part of the British sector, south of 56°N, is not proven according to Balson & Jeffery (1991) and Cameron et al., (1992). The authors conclude however that Middle Pleistocene sediments in the northern North Sea are present. This contrasts with earlier studies which suggested that the greater part of the Quaternary sediments in the northern North Sea were Middle to Late Weichselian.

Correlation with the glacial deposits on land in the northern Netherlands (Ter Wee, 1983b; Van den Berg & Beets, 1987) and northern Germany (Ehlers, 1990) indicate that the advance of Scandinavian ice in the North Sea took place during the Drenthe Glacial Stage.

The depth of boreholes and samples are given in metres below Mean Sea Level (MSL). The lower sample is quoted first and the upper sample second. For the location of boreholes, see Table 4.

5.2 Saalian sediments in the Dutch sector of the North Sea

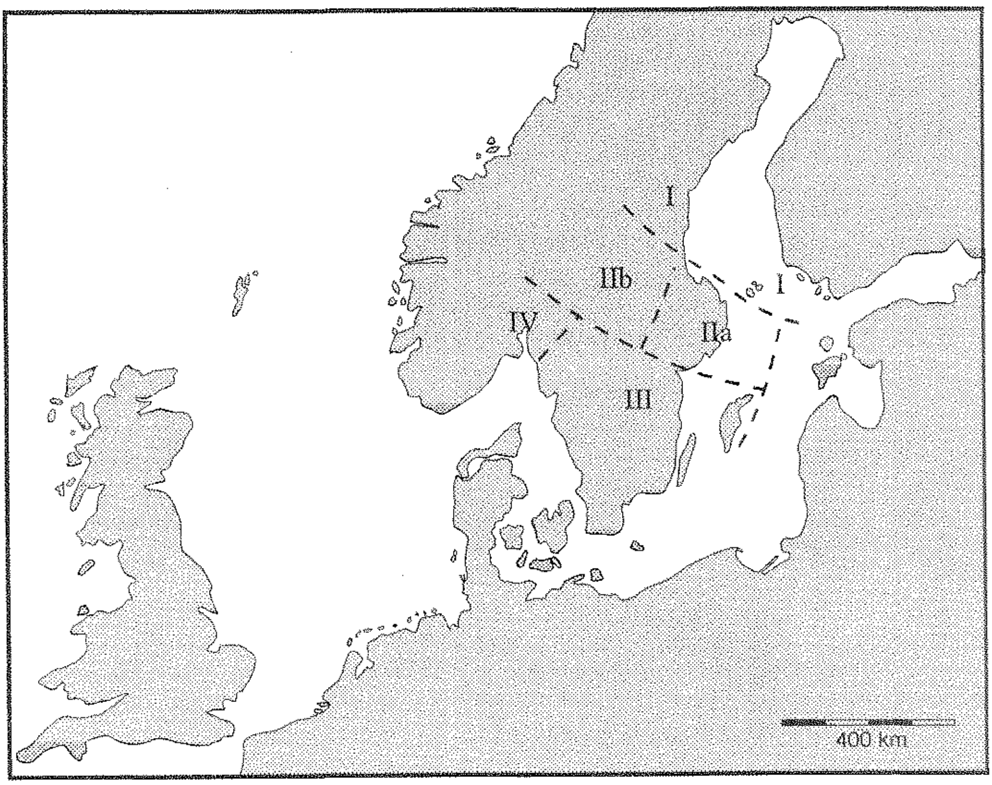
The sediments of the Saalian glacial and interglacial stages in the North Sea can be divided into four litho-stratigraphic units:

1. The Tea Kettle Hole Formation which is mainly represented by a build-up of (fluvio)periglacial deposits.
2. The Cleaver Bank Formation consisting of glaciolacustrine sediments, predominantly clay.
3. The Borkumriff Formation consisting of till and gravelly deposits.
4. The Molengat Formation consisting of fluvioglacial sand and gravel.

The relationships between the formations are shown in the Tables 10 - 13.

The glacial features which formed in the North Sea during the glaciation, and discussed below, include valleys (subglacial, ice-marginal, and tongue-shaped basins), esker-like phenomena, ice-pushed structures as for example ice-pushed ridges.

Fig. 31. The Roman figures indicate the Hesemann division of source areas of crystalline indicators: I. East-Baltic (mainly south-west Finland and Åland Islands), IIa. East-Central Baltic, IIb. West-Central Baltic, III. South-Baltic, IV. Oslo area (Hesemann, 1930).

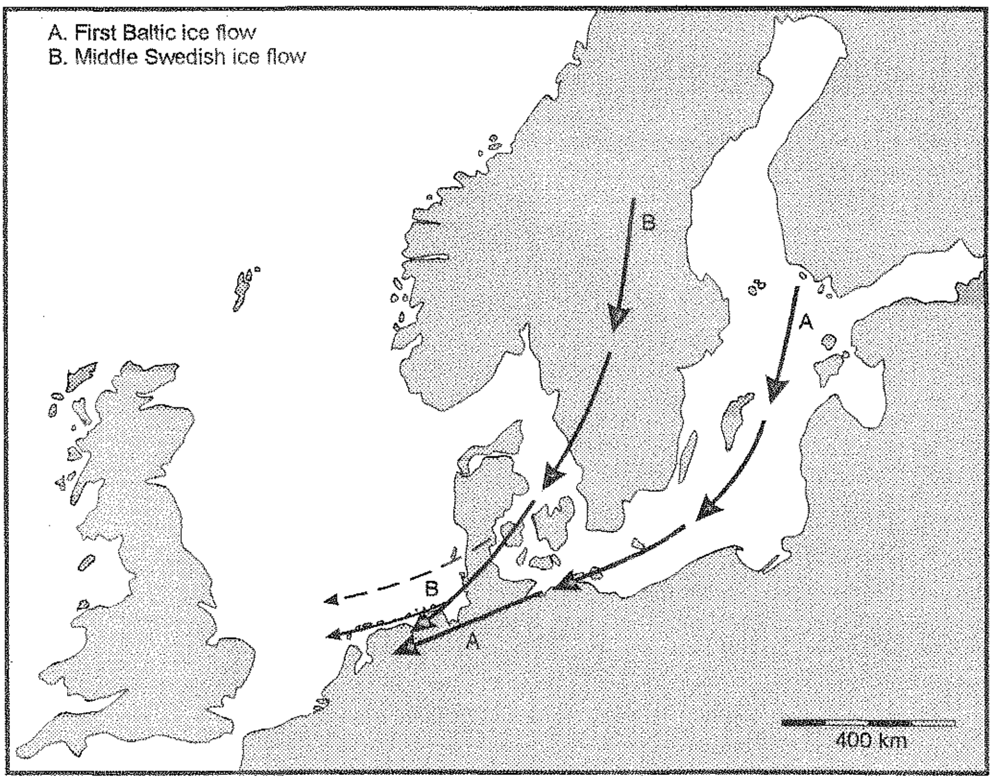


In the Netherlands at least five main flow directions of the Saalian ice sheet are recognised by Zandstra (1987). The directions are based on counts of crystalline Scandinavian indicator pebbles in tills, the erratic content being a characteristic of the source area and for the main flow directions of the ice sheets (Hesemann, 1930; Fig. 31). No so-called Hesemann counts have been carried out on material from the North Sea, because samples obtained by drilling are small and do not contain sufficient gravel for pebble counts. Higher percentages of gravel, ranging from less than 1% to 77.4%, are encountered in gravel deposits occurring at or near the sea bed in two areas, notably north-west of the island of Texel (in blocks L12, L14 and L15) and in an area in the south-east part of the Dutch sector, (in blocks G18 and N1) (Van der Klugt, 1991; Laban et al., 1995b).

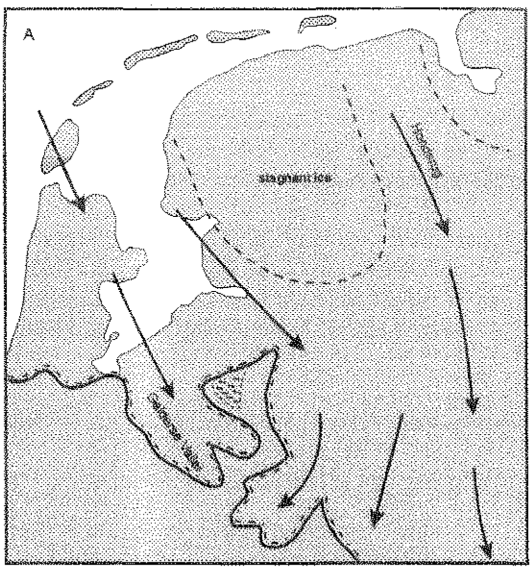
According to Rappol (Rappol, 1984; 1987; Rappol et al., 1989; Van den Berg & Beets, 1987) there are indications that ice entered the northern Netherlands from the North Sea area twice with flow directions respectively of north-south and north-west/south-east (Fig. 32).

Rappol et al. (1989, 1990) recognised three types of till deposited by different ice flows i.e. the First Baltic Till, the Swedish Till and the Second Baltic Till of the Older Saalian Glaciation (Drenthe Glacial Stage). The directions of ice movement have been recognised through morphological, petrographical, and clast fabric analyses of the till-sheet. Rappol et al. (1989)

Fig. 32. Generalized flow directions of the Saalian ice sheet during the south-westerly movement of the Drente Glaciation (after Rappol et al., 1989).



suggested that the main direction of the ice-flow during deposition of the First Baltic Till was north-east/south-west as far as the maximum extension of the ice sheet, whereas during deposition of the Second Baltic Till the ice-flow took a more north-west/south-east course. In the northern Netherlands large bodies of stagnant ice were present, pushing the ice stream into a channelled flow to the south-east (Fig. 33).
The relationship of these land tills with those of the North Sea tills are discussed below, when describing the Borkumriff Formation.



5.3 Periglacial sediments (Tea Kettle Hole Formation)

In this section the lithology, occurrence and stratigraphic position of the Tea Kettle Hole Formation in the North Sea and in The Netherlands is discussed.

5.3.1 Dutch sector

The oldest Saalian sediments encountered in the North Sea belong to the Tea Kettle Hole Formation (Cameron et al, 1986). The formation is named after the Tea Kettle Hole depression west of the island of Texel where the formation has been sampled in borehole K15-4.

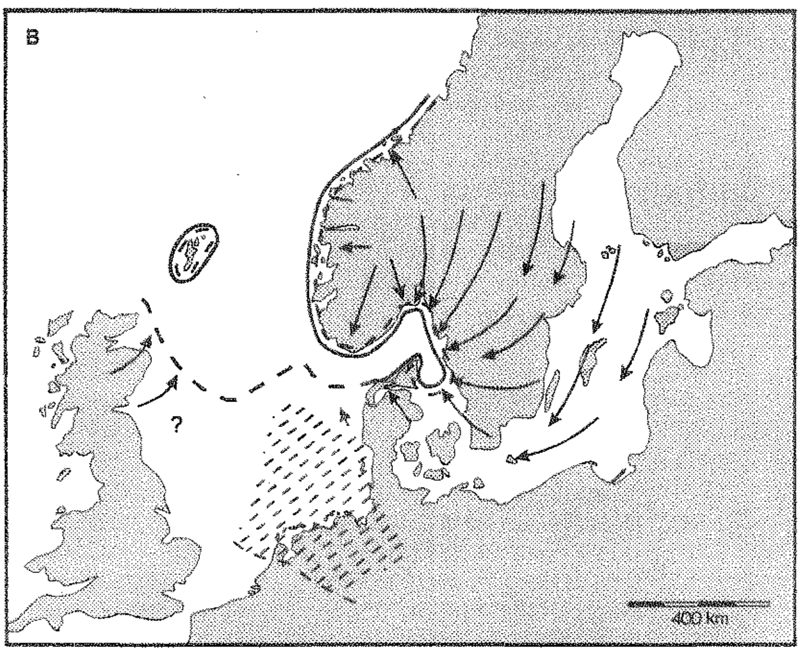


Fig. 33.
A. Reconstruction of ice movement during the deposition of the Second Baltic Till. The ice stream is channelled by the occurrence of areas with stagnant ice.

B. The ice flow after detachment of the ice sheet from its source caused by calving of the ice when it reached the Oslo fjord (after Rappol et al., 1989).

The deposits are sampled in more than 40 boreholes both within the area of maximum extent of the Saalian ice sheet and in a wide surrounding zone. In the "type locality" in borehole K15-4 the formation is present between 52.55 m and 45.15 m below MSL and consists of yellow-grey, very fine- to fine-grained, slightly silty sand, rich in $CaCO_3$. No pollen has been found in samples from this borehole (Zagwijn, 1977). The deposits are overlain by Weichselian periglacial and Eemian marine deposits and underlain by Holsteinian marine sediments.

The sediments in other areas consist mainly of very fine- to medium-grained (63-500 μm) sand. Locally they are slightly silty to silty with clay laminae, and may contain organic matter (wood fragments), mica, and fine gravel (Fig. 34). In areas where the top is not eroded the sands are mainly non-calcareous, but in the deeper sections they are locally slightly calcareous.

In the northern part of the Dutch sector, in borehole A5-9, the formation is present between 75.70 m and 69 m below MSL. Foraminiferal analysis on samples from this borehole revealed a reworked fauna with weathered boreal species, mainly *Ammonia beccarii*. The deposit is overlain by Eemian marine sediments of the Eem Formation and is underlain by Holsteinian marine sediments of the Egmond Ground Formation (Neele, 1990).

Farther south in borehole L4-21 very fine, silty, micaceous sand is present between 69 m and 63 m below MSL containing a high percentage of organic matter and charcoal fragments. The sand is underlain by Elsterian glaciolacustrine clay and overlain by Eemian marine sediments.

In borehole L11-8 grey, fine- to medium-grained, locally slightly silty sand is present between 50.50 m and 45.70 m below MSL underlying Saalian glaciolacustrine clay and overlying Holsteinian marine sediments. In borehole E1-10, drilled on the Dogger Bank, very fine, greyish-brown, silty, laminated non-marine sand with organic fragments, but free of $CaCO_3$, has been sampled between 70 m and 67 m below MSL. It is overlain by Saalian glaciolacustrine clay (Cleaver Bank Formation) and underlain by the Elsterian Swarte Bank Formation (Neele, 1986b; Sliggers & Meijer, 1987; Zagwijn, 1986). In borehole L2-1 the Tea Kettle Hole Formation is present at a depth of 75 m below MSL underlying 10 m of Saalian till. The thickness of the deposit is 2.50 m and it overlies the Egmond Ground Formation. Pollen analyses on samples from this borehole revealed an association containing a high percentage of herbs, while thermophilous trees are represented by *Alnus sp.* which points to a cool phase in the Early Saalian (Zagwijn, 1970a).

Still further south, and west of the island of Texel, olive-grey, micaceous, slightly glauconitic, calcareous, occasionally muddy, fine sand was sampled below Saalian till. Clay pebbles and blocks were found locally in the deposits (Sha et al., 1995). Pollen analyses of the clay sampled in boreholes L17-151 (28.20 m below MSL) and L18-83 (20.20 m below MSL) indicated a Late Holsteinian age (Cleveringa, 1991). Locally the deposits show deformation structures due to ice-pushing. It is very likely that clay lumps of the underlying Holsteinian deposits were incorporated into the periglacial sediments during deformation (Fig. 35).

The occurrence of the formation over such a large area is due to the presence of the cover of glaciolacustrine clay which protected the periglacial sands against post-Saalian erosion. The deposits mainly overlie Elsterian glaciomarine clays or Holsteinian marine deposits which thus exclude an Elsterian age. During the transition from the Late Elsterian to the Holsteinian a marine environment prevailed (see Chapter 4.5.5).

The southernmost occurrence of the formation is found in borehole P5-4. Here a layer of fine, yellow-grey, slightly silty sand containing organic matter is present between Eemian and

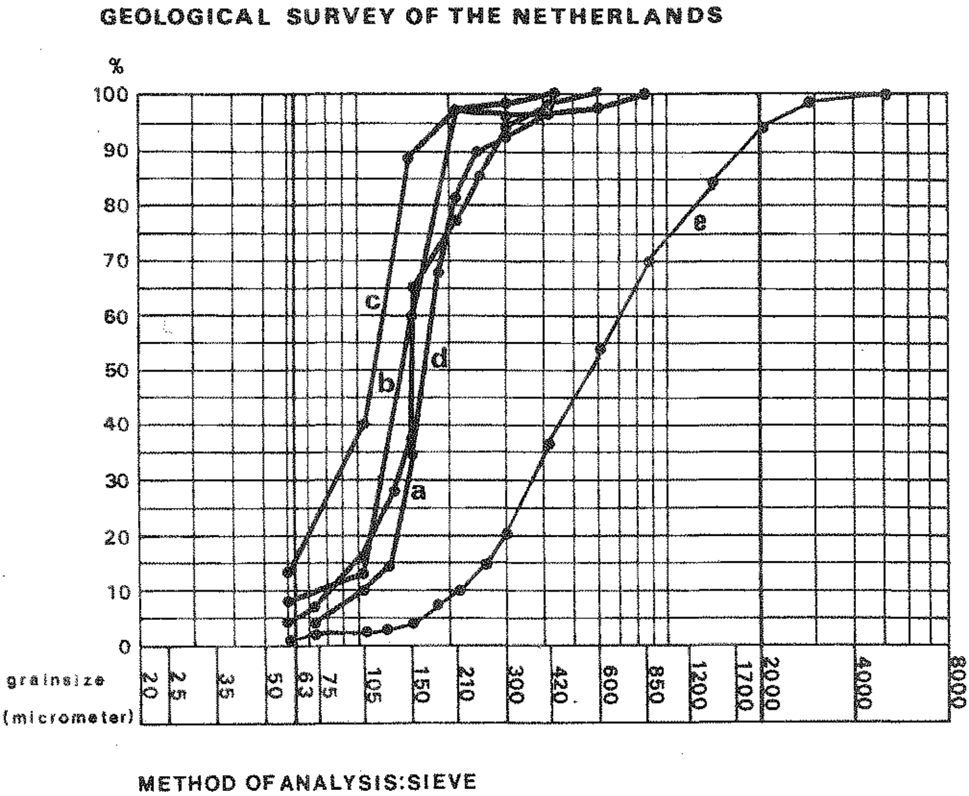


Fig. 34. Grain size analyses of the Tea Kettle Hole Formation in boreholes F14-4 (a), F17-9 (b + c) and M11-39 (d + e).

Holsteinian marine deposits (between 49.80 m and 45.80 m below MSL). The material at the top of the deposit is free of $CaCO_3$ but slightly calcareous below. The deposit, based on its stratigraphic position and lithology, is regarded as Saalian in age (Zagwijn, 1970c). The sand did not contain any diatoms or ostracods (Du Saar, 1970a).

The deposits of the Tea Kettle Hole Formation are mainly fluvio-periglacial, locally aeolian (grain size analysis of borehole F3-2, Fig. 34) and are probably derived from the fluviatile Yarmouth Roads Formation (Cromerian) and the marine Egmond Ground Formation (Holsteinian).

The thickness of the formation varies considerably and ranges generally from 3 m to 16.60 m but exceptionally a thickness of 27.50 m has been recorded. The depth to the top of the formation varies from 14.80 m to 36.30 m in the coastal areato 71.15 m below MSL in the northern area (A-blocks). The deepest deposits are found in block L2 at 74.60 m below MSL. In this block borehole L2-19 was drilled in an Elsterian valley filled with Elsterian glaciolacustrine Swarte Bank Formation and Holsteinian marine Egmond Ground Formation. At the end of the Holsteinian a depression remained which, during the Saalian glaciation, was

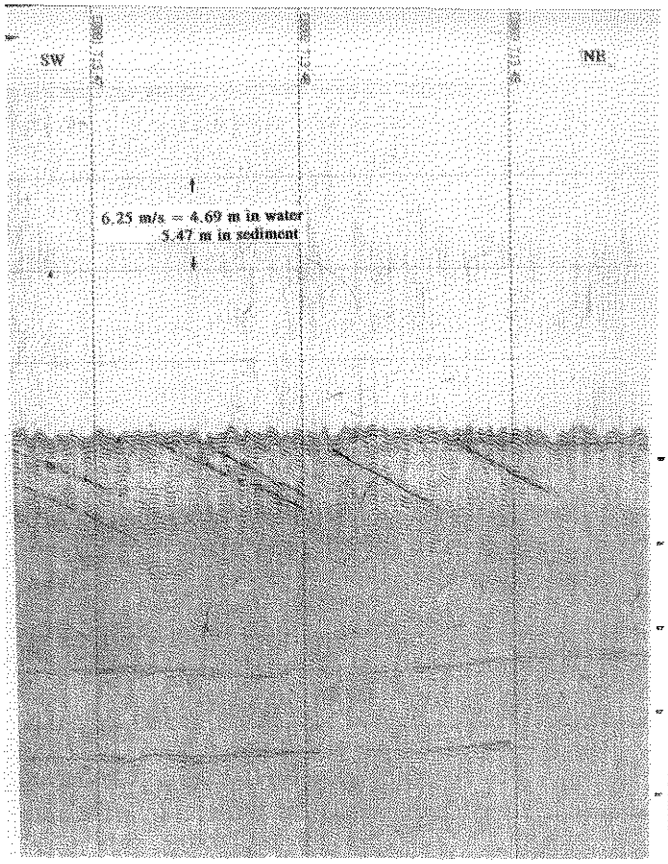
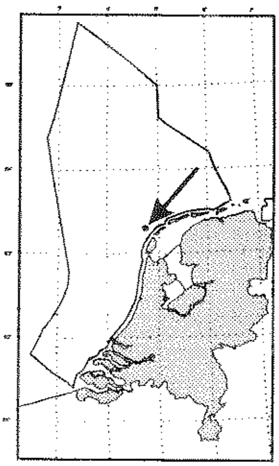


Fig. 35. High resolution seismic profile 3.5 kHz (ORE-180) from near the island of Texel (line 3: plot numbers E0081E0083) showing deformation structures in the Tea Kettle Hole Formation caused by ice-pushing.



Photograph J.M.P.K. van Delft.

filled with fluvio-periglacial sand and covered by fine, very dense aeolian sand. The thickness of the deposits in this borehole is 8.50 m.

In the eastern L blocks and in most of the M-blocks there is a lack of information because only a few deep boreholes were drilled in these blocks.
Presumably the distribution of the sediments is much more widespread, and extend into the British sector. According to Cameron et al., (1989) and Cameron et al., (1992) the formation is so thin in the British sector that its presence is generally undetectable on seismic profiles.

On the high resolution seismic profiles in the Dutch sector the formation is clearly visible only in the southern K-blocks (Cameron et al., 1986) and in the southern G-blocks (Laban et al., 1995a). In these blocks the formation locally forms a continuous layer with a thickness varying from less than 1 m to about 10 m and overlies the marine Egmond Ground Formation (Holsteinian). The depth of the top in these blocks varies between 50 m and 44 m below MSL. Within the formation no internal reflections are observed. Fig. 36 shows the geometry and depth to the top below MSL of the Tea Kettle Hole Formation.

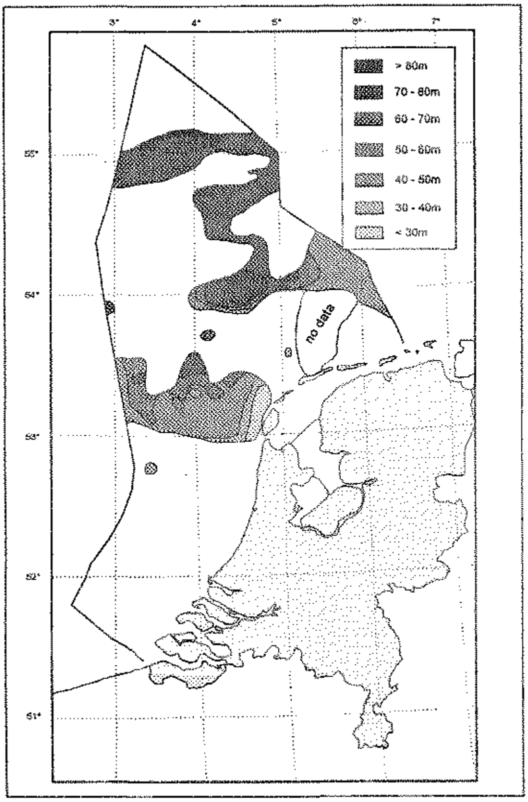


Fig. 36. The geometry and depth to the top of the Tea Kettle Hole Formation in metres below MSL.

5.3.2 The Netherlands

In the Netherlands comparable deposits have been found. They are referred to the Eindhoven Formation (Van der Toorn, 1960). From pollen analysis investigations in the northern Netherlands, Zagwijn (1973) concluded that cold climatic conditions prevailed during the deposition of the formation resulting in an alternation of open landscapes or polar deserts with permafrost and a subarctic vegetation. Such conditions would have predominated during at least three Saalian stadials according to Zagwijn. Ter Wee (1966) suggested that the sand represented the fine fractions of the fluviatile formations of Enschede (Elbe, Weser) and Urk (Rhine). Ter Wee supposed the fine fractions had been washed out by local streams or locally blown by the wind.

In the western Netherlands the top of formation is present at a depth of between 35 m and 40 below NAP and reaches thicknesses of up to 10 m (Westerhoff et al., 1987)

During the Saalian Hoogeveen and Bantega interstadials in the northern Netherlands, temperate zone forests covered the landscape. The Hoogeveen Interstadial correlates partly with the Schöningen Interstadial in Germany. Peat datings of this interstadial by the U/Th method revealed preliminary ages of 180 and 227 ka which correlate with the Early Saalian (Urban, 1995).

Sediment petrological analyses of samples of the Eindhoven Formation in an excavation in the northern Netherlands near Peelo, recorded a heavy mineral assemblage consisting of about 85% (garnet 38 to 71%) of garnet, epidote, hornblende and alterites (Zandstra, 1975). Heavy mineral analyses of samples of the Eindhoven Formation from borehole 9D/181 near Den Burg (Texel) also revealed an association with garnet and which is typical of this formation (Zandstra, 1975; 1977a).

The Tea Kettle Hole Formation has the same genesis and has a similar lithology to the Elsterian Middelrug Formation and the Weichselian Twente Formation. On seismic profiles it is very difficult to distinguish between these formations.

The age of the formation in the North Sea is Early to Late Saalian prior to the glaciation. Periglacial deposits post-dating the Saalian glaciation have not been found.

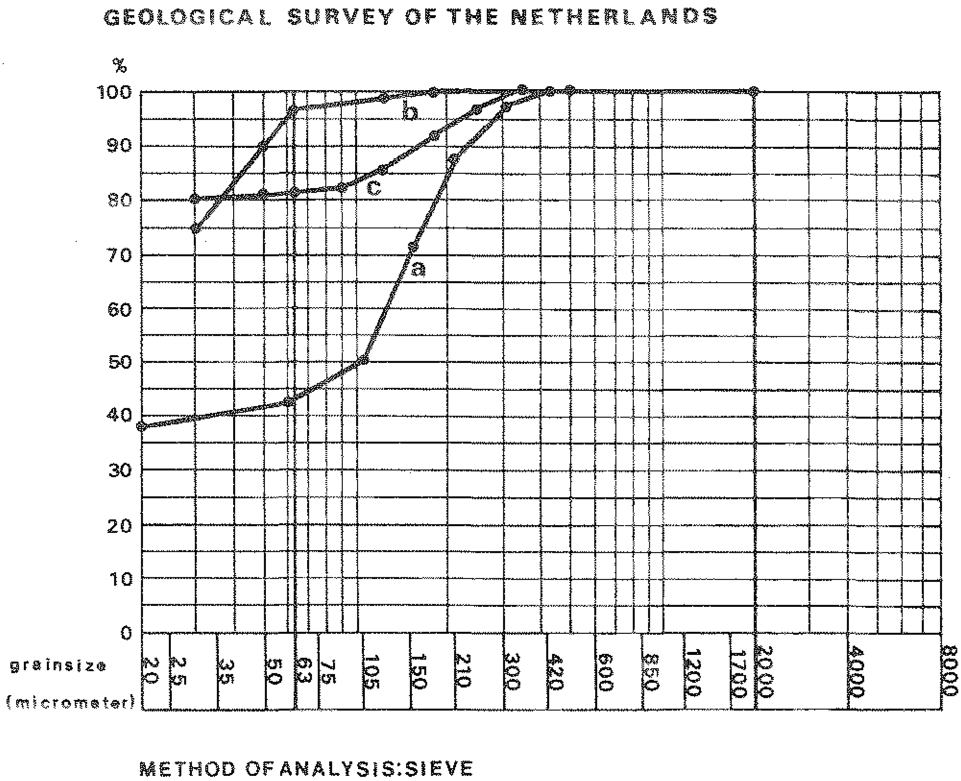
5.4 Glaciolacustrine sediments (Cleaver Bank Formation)

5.4.1 Dutch sector

During the maximum extent of the Saalian ice sheet a vast lake was present in front of the ice margin and this margin extended far to the west into the British sector to at least as far north as 55° 40' N. In the pro-glacial lake glaciolacustrine clays and fine-grained silty sands were deposited (Fig. 37), and are referred to the Cleaver Bank Formation (Cameron et al., 1986). The formation is named after the Cleaver Bank in the Dutch sector, north-west of the Dutch coast. Here, according to the high resolution seismic profiles, it is present just below the sea bed under a thin cover of <2 m of Holocene sediments. The formation was sampled at that location in shallow core K4-3.

In the Dutch sector the Cleaver Bank Formation is found in a large number of boreholes and can also be easily distinguished on the high resolution seismic profiles. A number of boreholes in which the formation was sampled is discussed below.

Fig. 37. Grain size analysis of the Cleaver Bank Formation in boreholes F17-9 (a) and Q3-51 (b + c).



In borehole E1-10 the Cleaver Bank Formation is present between 67 m and 44.40 m below MSL and consists of dark-grey stiff, calcareous clay locally with silt lenses. At some levels fine gravel, most likely representing dropstones, is present. The clay is underlain by the periglacial sediments of the Tea Kettle Hole Formation and overlain by the Weichselian glaciolacustrine clays of the Dogger Bank Formation. Foraminiferal analysis of the clay revealed a poor fauna indicative of a non-marine environment of deposition (Neele, 1986b). No molluscs were found (Sliggers & Meijer, 1987). Pollen analysis revealed a Scandinavian glacigenic influence (Zagwijn, 1986). X-ray photographs of 15 samples from this borehole have been made which reveal a massive homogeneous structure, locally laminated, and occasionally interrupted by angular dropstones (Fig. 38).

The northernmost borehole in which the Cleaver Bank Formation was sampled is A9-9. Here the deposits are present close to the sea bed (between >10 m and 7 m below sea bed with the upper surface at 42.30 m below MSL). They are overlain by Eemian marine and Weichselian periglacial deposits. The Eemian mollusc fauna which has been found comprises typical Eemian species like *Flexopecten flexuosa, Venerupis aurea senescens* and the estuarine species of *Corbicula fluminalis* (Meijer, 1989).
South-west of borehole A9-9 the Cleaver Bank Formation is overlain by the Weichselian glaciolacustrine Dogger Bank Formation, samples of which can hardly be distinguished by eye from the Cleaver Bank Formation. However the two formations can be distinguished quite clearly on the seismic profiles.

Somewhat further to the south-east, in borehole B13-5, the top of the clay lies at only 0.90 m below sea bed (46.10 m below MSL). The base of the clay was reached at 75.38 m below MSL. Pollen analyses of 8 samples revealed that much of the pollen consists of reworked Miocene and Pliocene material. In this clay, however, a high percentage of pollen from herbs (*Artemisia*) is also found indicative of an open landscape during deposition (Zagwijn, 1971b). The clay is underlain by sand, at least 17.22 m thick and which extends from 92.60 m to 75.38 m below MSL at the base of the borehole. The sand is fine- to very fine-grained with silt laminae and shell fragments. According to the pollen record (Zagwijn, 1971b) this sand is of fluvioglacial origin and has the same pollen content as the overlying clay. Probably the sand is derived from reworked Holsteinian Interglacial or older marine deposits. Heavy mineral analysis on 6 samples of this sand revealed an association with garnet, epidote, hornblende and 1.5% to 3.5% of augite and, in one sample, up to 1% topaz. Because of this association Zandstra (1971b) concluded that the sand is not older than Middle Pleistocene and consists of reworked fluviatile deposits of the Urk Formation (Zonneveld, 1958).

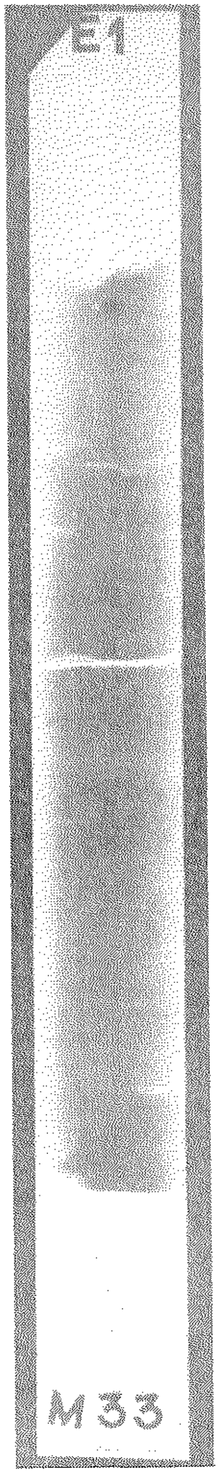


Fig. 38. X-ray photograph of the Cleaver Bank Formation in borehole E1-10 showing parallel and subparallel laminae.

5.4 Glaciolacustrine sediments (Cleaver Bank Formation)

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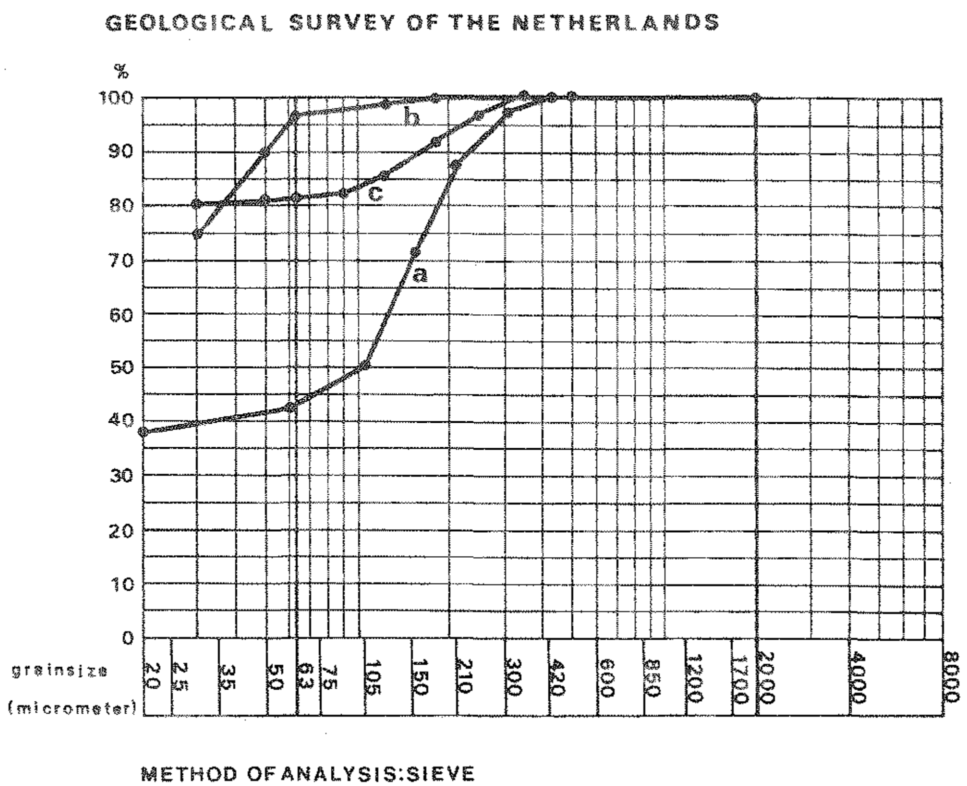

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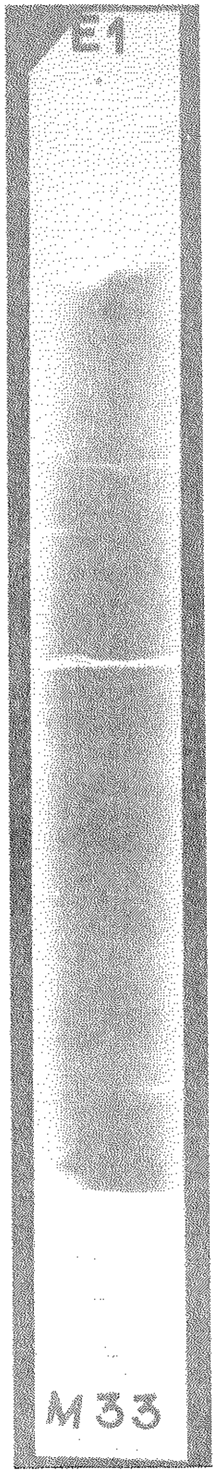

Fig. 38. X-ray photograph of the Cleaver Bank Formation in borehole E1-10 showing parallel and subparallel laminae.

North-east of borehole B13-5, and in the Danish sector a number of deeper boreholes (Roar 41/43; Skjold 21, Dan 31 and Nordsø A1-A2) have been drilled. Knudsen (1985, 1986) made a stratigraphical interpretation of the Roar, Skjold and Dan boreholes based on foraminiferal analyses. She interpreted the sediments in the Roar borehole using shallow marine faunas, i.e. zone R4, referred to the Eemian and further correlated with the S3 (Skjold) and D3 (Dan) marine zones. The underlying zones are regarded as older glacial deposits, presumably of Saalian age. A sample of the Saalian deposits of the Roar 41 borehole was dated by amino acid analysis and appeared to be of Early Eemian or Late Saalian age (Sejrup & Knudsen, 1993).
Bertelsen (1972) analyzed two deeper boreholes in the southern part of the Danish sector (Nordsø A1 and A2) based on the presence of megaspores of *Azolla* species (see Chapter 3.1). No evidence was found for the presence of Saalian glacial and Holsteinian/Eemian marine sediments. However, he interpreted a clay unit, reflected on the gamma log between c. 46 m and 30 m below sea bed as probably having been deposited during the Elsterian glaciation by correlation with glaciolacustrine clays in the Dutch sector previously dated as Elsterian by Oele (1969). Since it is now known that the deposits in the Dutch sector are of Saalian age, it is more than likely that the deposits in the Danish sector are also Saalian.
On the gamma ray log in Nordsø A1 borehole above the clay unit, a sandy unit is present which may be an Eemian marine deposit. The gamma ray log of Nordsø A2 borehole indicates a complete clay unit overlain by Weichselian and Holocene sediments (Bertelsen, 1972).

In borehole E8-4 the formation was sampled between 52.80 m and 68.73 m below MSL, and consists of a very stiff, brownish-grey clay with, at the top, some gravel (ice-rafted debris). The clay is underlain by marine Holsteinian and overlain by the Weichselian glaciolacustrine Dogger Bank Formation. Based on the presence of only a few foraminifera the material between 59.50 m and 52.90 m below MSL is regarded as probably non-marine (Neele, 1986a). However, in the sediment between 57.60 m and 54.80 m below MSL a marine mollusc (*Yoldia*, indet.) was found suggesting a marine intercalation (Sliggers & Meijer, 1987). The pollen content is largely reworked and is of Scandinavian provenance (reworked Miocene and Pliocene material) but with an increasing British influence towards the top (Zagwijn, 1986). As mentioned above, the Cleaver Bank Formation is overlain by the Dogger Bank Formation in this borehole and it is probable that the upper part belongs to this formation.

In borehole F3-2 between 79.10 m and 65.60 m below MSL a light grey to dark brown, stiff, calcareous clay with silt laminae was sampled. The clay is underlain by periglacial deposits of the Tea Kettle Hole Formation and overlain by fluvioglacial sand referred to the Saalian Molengat Formation (Joon et al., 1990). Pollen analysis revealed reworked Miocene and Pliocene pollen of Scandinavian provenance (Zagwijn, 1970d).

Towards the northern part of the Dutch sector, near to and north of 55°N and east of 4°E, the formation is present close to the sea bed.
In borehole K1-10 between 70.15 m and 61.15 m below MSL a brown, very silty, very stiff clay was sampled overlain by marine Eemian sediments and underlain by marine sediments which probably belong to the Holsteinian Interglacial. Pollen analysis confirmed the Eemian age of the overlying deposits and revealed a high percentage of not only different Tertiary pollen, but also of older pollen which, according to De Jong (1981b), is all of British

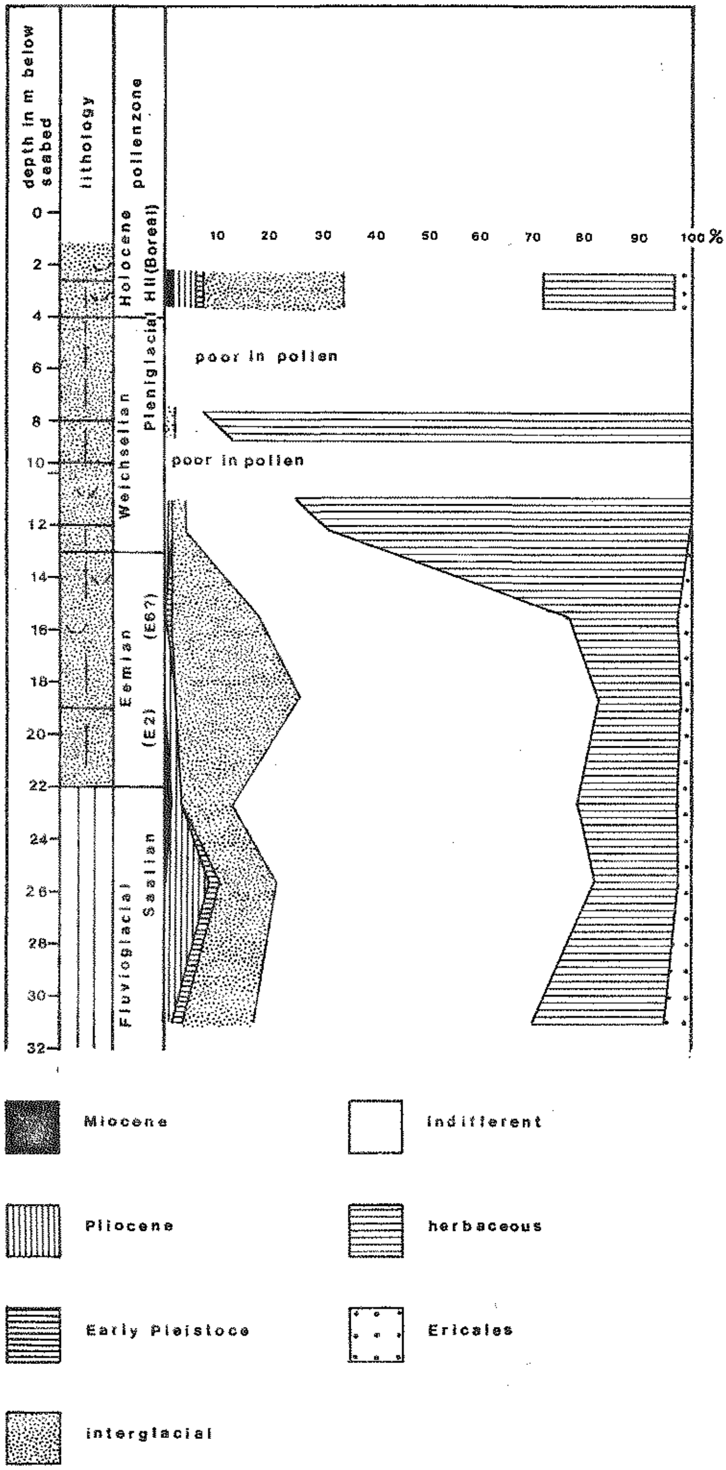

Fig. 39. Pollen spectrum of Saalian glaciolacustrine sediments in borehole KI-10 (De Jong, 1981a).

North-east of borehole B13-5, and in the Danish sector a number of deeper boreholes (Roar 41/43; Skjold 21, Dan 31 and Nordsø A1-A2) have been drilled. Knudsen (1985, 1986) made a stratigraphical interpretation of the Roar, Skjold and Dan boreholes based on foraminiferal analyses. She interpreted the sediments in the Roar borehole using shallow marine faunas, i.e. zone R4, referred to the Eemian and further correlated with the S3 (Skjold) and D3 (Dan) marine zones. The underlying zones are regarded as older glacial deposits, presumably of Saalian age. A sample of the Saalian deposits of the Roar 41 borehole was dated by amino acid analysis and appeared to be of Early Eemian or Late Saalian age (Sejrup & Knudsen, 1993).
Bertelsen (1972) analyzed two deeper boreholes in the southern part of the Danish sector (Nordsø A1 and A2) based on the presence of megaspores of *Azolla* species (see Chapter 3.1). No evidence was found for the presence of Saalian glacial and Holsteinian/Eemian marine sediments. However, he interpreted a clay unit, reflected on the gamma log between c. 46 m and 30 m below sea bed as probably having been deposited during the Elsterian glaciation by correlation with glaciolacustrine clays in the Dutch sector previously dated as Elsterian by Oele (1969). Since it is now known that the deposits in the Dutch sector are of Saalian age, it is more than likely that the deposits in the Danish sector are also Saalian.
On the gamma ray log in Nordsø A1 borehole above the clay unit, a sandy unit is present which may be an Eemian marine deposit. The gamma ray log of Nordsø A2 borehole indicates a complete clay unit overlain by Weichselian and Holocene sediments (Bertelsen, 1972).

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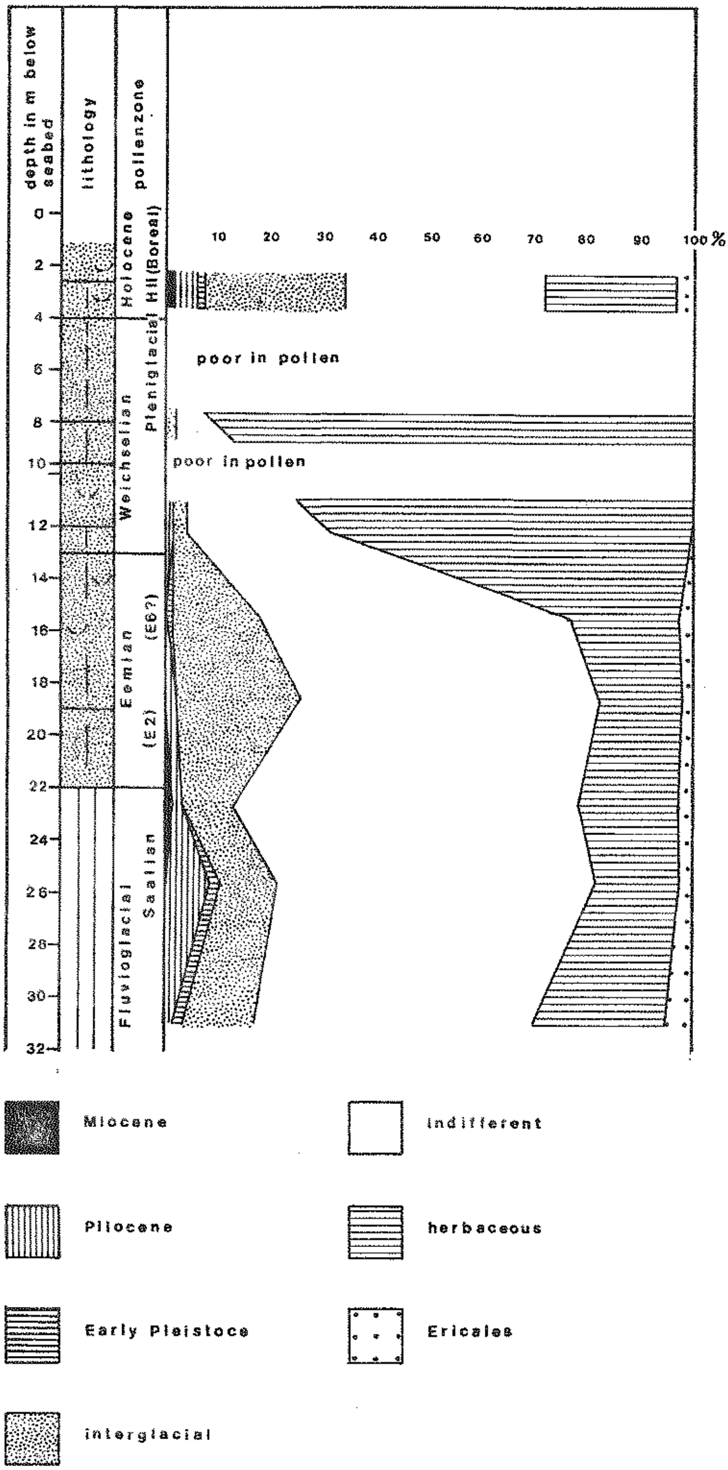


Fig. 39. Pollen spectrum of Saalian glaciolacustrine sediments in borehole KI-10 (De Jong, 1981a).

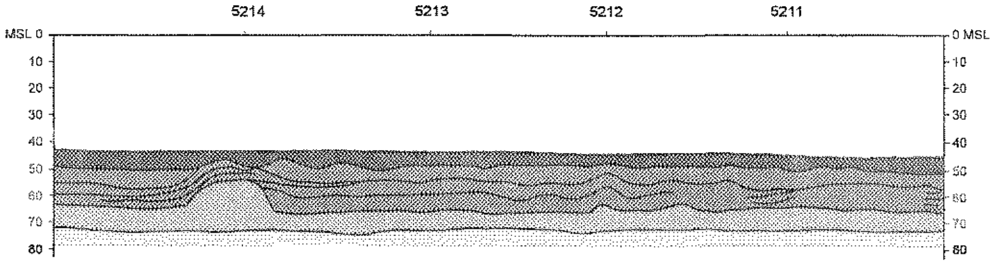
provenance. This pollen analysis is atypical in that it differs from the others which all contain Tertiary pollen with a Scandinavian provenance. There are no indications of the presence of vegetation during the deposition of the clay (Fig. 39).

In borehole L11-8 between 57.70 m and 50.50 m below MSL the formation consists of a very silty, sandy, medium stiff grey clay with silt laminae. This borehole was drilled within the area once covered by ice, and the clay must have been deposited during the advance of the ice sheet.

In borehole Q3-51, drilled near the coast of the island of Texel, the formation was sampled between 57 m and 35.20 m below sea bed. The borehole was probably drilled in a subglacial valley. Because of the shallow water depth of only 2.90 m no successful seismic survey could be carried out at this site. The formation is overlain by the Eem Formation and underlain by the Egmond Ground Formation.

A method of distinguishing between sediments of different provenance is possible by trying to establish their molecular characterization. The results however are not entirely understood and are not wholly satisfactory. The composition and distribution patterns of organic compounds present in direct extracts and extracts obtained after acid and base hydrolysis are analyzed by chromatography (GC) and gas chromatography mass spectrometry (GS-MS). In this case six samples were selected which belong respectively to the Dogger Bank Formation (British provenance), the Cleaver Bank Formation (Scandinavian provenance) together with three samples in which it was uncertain to which of the two formations they belong. According to De Leeuw & Baas (1993) a careful inspection of all gas chromatograms revealed that the distribution patterns of the alkanes, the alkanols and the alkanoic acids changed considerably. The changes however could not be correlated and cannot be ascribed to differences between the two formations. The differences may originate from varying sources of plant waxes, different transport mechanisms, depositional environments etc. The investigators therefore conclude that the results of these detailed lipid analyses do not enable a straightforward separation to be made between North Sea sediments of British (Weichselian) or Scandinavian (Saalian) provenance.

In block A15 a number of ridge-like structures can be seen on the seismic profiles and these range in height from 2 m to c. 10 m. No reflector is present at the base to indicate that they were formed during the deposition of the Cleaver Bank Formation. Hyperbolic reflections indicate the presence of gravel and boulders. There is no borehole information to prove the sedimentary content. On the seismic profiles the overlying Dogger Bank Formation (see 6.4) shows draped reflections over the structures (Fig. 40). A possible explanation for their genesis is so-called icing (naledi or aufeis). Icings are extensive ice bodies which can be formed in front of glaciers. They can be fed by both meltwater and groundwater released by the direct or indirect actions of glaciers. Superficial drainage, especially during the summer, takes place mainly through channels which are cut into the surface of the icing; meanders are also formed. During periods of high discharge large quantities of meltwater transport sediments through the channels which subsequently become infilled. After melt down of the icing an esker-like landform is left behind (Fig. 41) (Åkerman, 1982).
The meltwater discharged by glaciers can be loaded heavily with debris of all grain sizes. Recent studies in eastern Canada showed that sediment-laden floating ice and icebergs transport yearly millions of tons of terrigenous sediments into marine, lacustrine and fluvi-



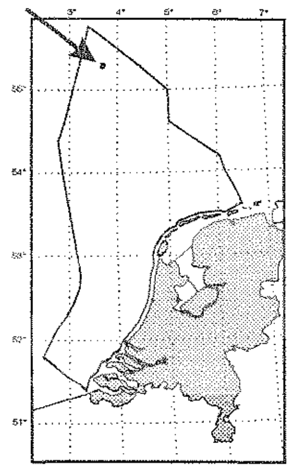


Fig. 40. Interpretation of a seismic profile showing ridgelike structures (icings or naledi) at the top of the Cleaver Bank Formation in block A15.

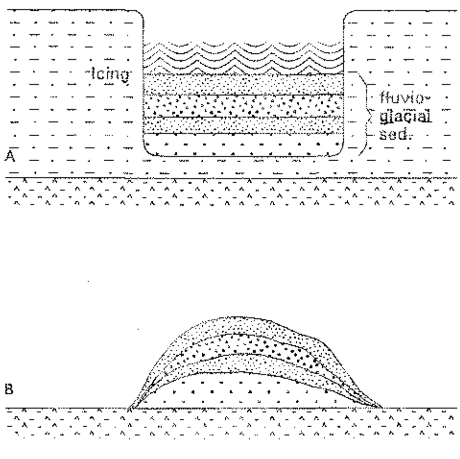


Fig. 41. Schematic drawing of the formation of an 'naledesker' in a superficial drainage channel.
a. during the existence of the icing and b. after melting of the icing (after Åkerman, 1982).

al environments (Dionne, 1993). The age of the structures is probably Late Saalian, but a Late Weichselian age can not be excluded.

The western margin of the lake in which deposition of the Cleaver Bank Formation took place was in the British sector and the deposits were laid down on the surface of gently eastward dipping pre-Saalian sediments. It is not clear what kind of barrier dammed the lake towards the north, but most probably in the Norwegian and Danish sectors, the Scandinavian ice sheet itself blocked drainage in that direction. The presence of Saalian ice in the northern part of the North Sea has been described by several authors. In the British sector, and to the north of the A blocks in the Dutch sector, the Fisher Formation has been mapped (Fyfe, 1986) by seismic profiling. The formation consists of very stiff, overconsolidated clay, silt and shelly sand. According to Fyfe the clay contains pebbles, which include

chalk. The formation has an average thickness of 50 m and is regarded as glaciomarine, possibly intertidal, and of Late Saalian age although no age-diagnostic fauna has been recovered.

In borehole 81/26 in the British sector north-west of Aberdeen 40 m of till was sampled which was probably deposited as a basal till during one or more of the Saalian glacial advances between 130 and 200 ka ago (Lithozone D). The dating of the till is based on amino-acid data from fragments of *Arctica islandica* (Sejrup et al., 1987). According to Andrews et al. (1990) the Saalian Fisher Formation, in the inner Moray Firth north-west of Aberdeen, was covered by ice during the Late Saalian. Here marine Saalian deposits are overlain by glacial and glaciomarine sediments; areas of ice-push deposits have also been noted.

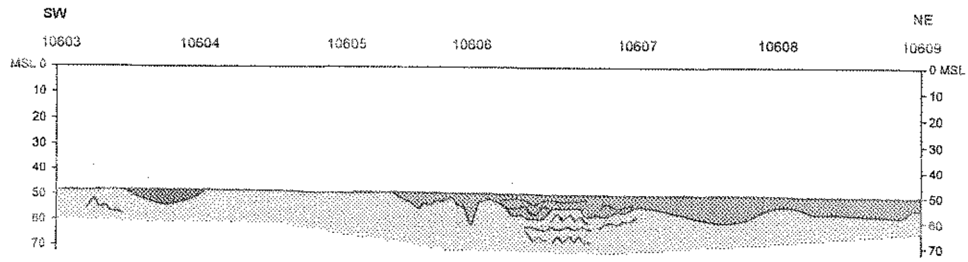
Oele (1969) interpreted the glaciolacustrine deposits as Elsterian in age. He regarded the clays over the entire area as one deposit and correlated the top of the clay in block G10 with the top of the Elsterian Peelo Formation present on the island of Ameland. Moreover he correlated the sequence of till overlying glaciolacustrine clay in the Dutch sector with that in the northern Netherlands which was also deposited during the Elsterian glaciation. Investigations have since shown that in the north-western part of the Dutch sector the till and glaciolacustrine clay present near sea bed were deposited during the Weichselian glaciation (Veenstra, 1965; Cameron et al., 1986) (see Chapter 6).

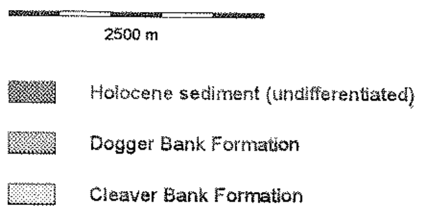
On the high resolution 3.5 kHz seismic profiles the Cleaver Bank Formation is easily interpreted, although the base is not always visible. The formation is predominantly thin, and forms an almost continuous layer with an average thickness of 3 m to 8 m underlying the Eem Formation. In the area south of about 55°N no internal reflectors are visible within the formation. Some channeling has been observed only locally (e.g. block F4). North of 55°N the formation thickens, its surface lying near or almost at sea bed (Jeffery et al., 1991). In this area horizontal and subhorizontal seismic stratification is present. The sediments are mainly overlain by the Weichselian Dogger Bank Formation. Thin erosional relicts of the Eem Formation are intercalated very locally (e.g. borehole A12-2). In the northern A-blocks A5 and A9, features are observed which can be ascribed to ice-pushing from the north during the Weichselian ice advance (Fig. 42) (see Chapter 6).

Fig. 43 shows the geometry and depth to the top of the Cleaver Bank Formation below MSL.

5.4.2 Northern and western Netherlands

The onshore glaciolacustrine clays in the Netherlands are referred to the Drente Formation (Van der Heide & Zagwijn, 1967) which, apart from till, also comprises fluvioglacial deposits and gravel and boulders left behind after the melting of the ice sheet. The Saalian glaciolacustrine deposits consist mainly of clay in which rhythmites, possibly varves, are found locally. These deposits have formed only in glacial lakes and basins. Pollen analyses show that the pollen content consists of reworked Tertiary material (Zagwijn & Van Staalduinen, 1975).
The most detailed study of a Saalian basin has been carried out in the Amsterdam Glacial Basin (De Gans, 1991; De Gans et al, 1987). Besides a discontinuous till bed at the base overlain by deltaic sediments and mass flow deposits, the lower part of the infill also con-





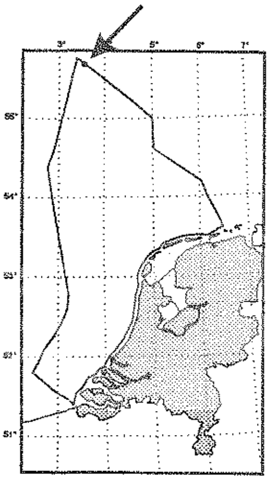
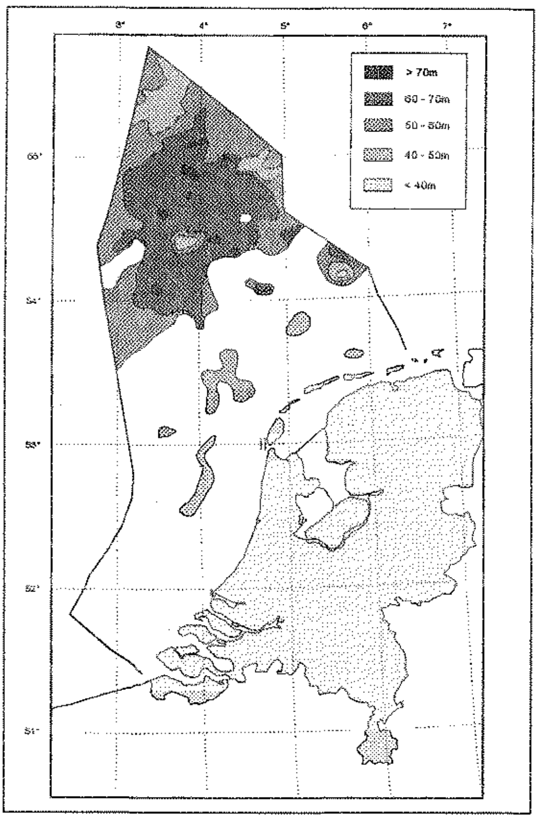


Fig. 42. Interpretation of a seismic profile showing icepushed structures in the Cleaver Bank Formation in block A-5.



sists of 3 m of varved clay (60-100 varves) overlain by a layer of glaciolacustrine clay with a thickness ranging from 25 m to 40 m. The top of the clay lies at 40 m below Ordnance Datum (NAP).

In the northern Netherlands the Saalian glaciolacustrine deposits consist predominantly of clay and silt, but locally also comprise coarse gravelly sand. The heavy mineral content indicates reworking of older Pleistocene deposits. No Tertiary components, as are present in the comparable Elsterian deposits, have been found (Zandstra, 1983b).

Fig. 43 Geometry and depth to the top of the Cleaver Bank Formation in metres below MSL.

5.5 Tills (Borkumriff Formation)

5.5.1 Dutch sector

Till, belonging to the Borkumriff Formation (Joon et al., 1990), has been sampled in several boreholes and cores in the area between the Frisian Islands and the southern F and G blocks as well as to the west of the island of Texel and in the Ems estuary. The formation is named after the Borkumriff Grund in the western part of the German sector of the North Sea where the till is present close to the sea bed.

In the Dutch sector of the North Sea the till consists of two facies: greenish-grey to dark brown-grey, sandy, between 10 and 20%, locally up to 36%, of the fraction <63 μm and 3% or less, angular to subangular matrix-supported gravel of Scandinavian origin which is found in the west. The second till facies in the east is more gravelly, consisting of greenish-grey, sandy, and with up to 47% of matrix-supported Scandinavian gravel.
The thickness of the till varies between <1 m and 10 m. The till is underlain respectively by:

- the Elsterian Swarte Bank Formation
  (e.g. boreholes N9-10, 11, 15, 20, 24, 25, 26, 32 and 33, N12-3, 8, 12, 14, 19-22).

- the Holsteinian Egmond Ground Formation (e.g. borehole L15-46).

- the Tea Kettle Hole Formation (e.g. boreholes L15-65, N9-12, 30, N12-11, 15, 23).

- the Cleaver Bank Formation (e.g. borehole L2-1).

The till is overlain by the Eem Formation and/or the Twente Formation (N12-3) as well as by Holocene sediments.

Pollen analysis on samples of the till in borehole L2-1 revealed high percentages of Tertiary pollen (mainly Miocene and Pliocene) and only a few Mesozoic pollen thus pointing to a Scandinavian provenance (Zagwijn, 1970b).
In borehole L11-7 the till is present between 38 m and 36 m below MSL and consists of very silty, sandy, stiff grey clay, with matrix-supported chalk fragments, overlying the Egmond Ground Formation.
Borehole M9-11 between >39.40 m and 38.60 m below MSL contains a greenish-grey, clayey, sandy till which is poor in gravel with only a few matrix-supported fine chalk fragments. Grain size analysis of the till reveals a clay/silt percentage of 36.2 % and 2 % fine gravel varying in size between 2 and 8 mm. The D50 of the sand fraction is 201.3 μm. The till is overlain by a 2.40 m thick layer of Eemian marine clay (Fig. 44).
In borehole M13-8 the till consists of sandy silt with pebbles (2 to 5 mm in diameter) intercalated with some thin layers (0.22 and 0.3 cm) of respectively medium sand (210 to 600 μm) with fine gravel and very to fine sand (75 to 150 μm). In borehole N9-8 from >19.40 to 18.40 m below MSL a silty, sandy till is present containing much matrix-supported crystalline, sedimentary and flint gravel. The clay-silt content of the till is 18.1 %. The gravel content however is 46.3 % and the size ranges between 2 and 31.5 mm. The D50 of the sand fraction is 308.8 μm (Fig. 44).
In borehole N9-35 between 17.30 m and 14.50 m below MSL a firm sandy and gravelly till

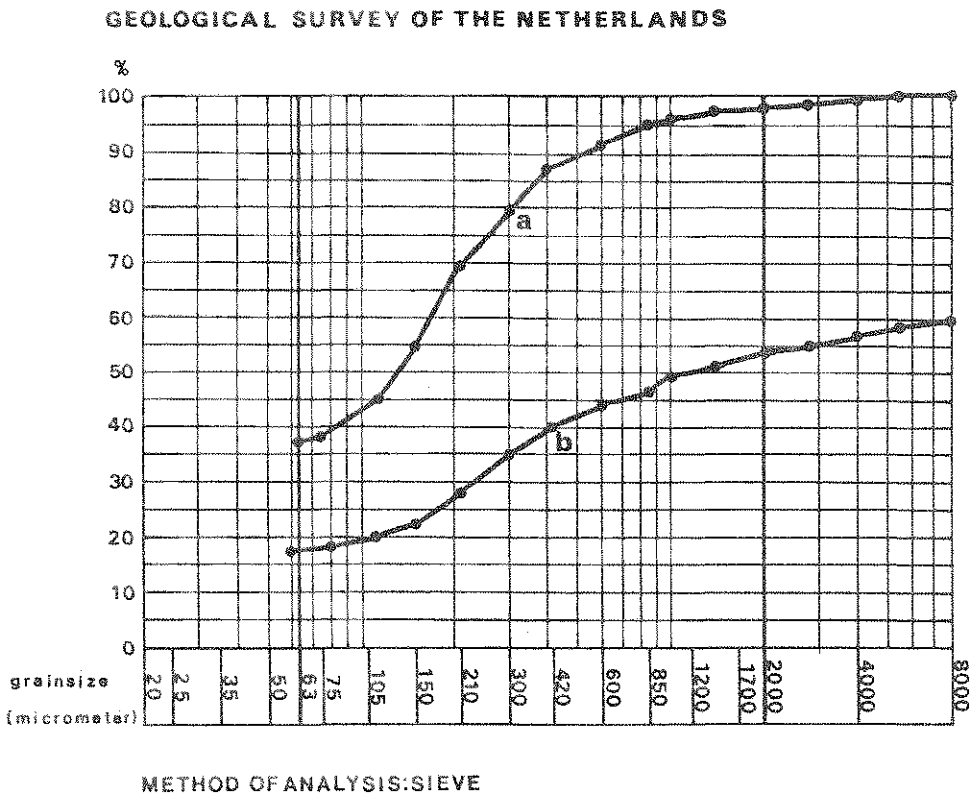


Fig. 44. Grain size distribution of the Borkumriff Formation sampled in boreholes M9-11 and N9-8 in the area north of the Frisian Islands.

is present which is intercalated with a layer of very fine to fine sand with coarse grains and gravel.
Heavy mineral analysis of a till sample from this borehole was carried out by Dijkmans (1981). The fractions between 53 and 300 μm contain 8-15% garnet, 6-32% epidote, 32-46% amphibole and 2-18% alterite (increasing in the coarser fractions) (Fig. 45a).

In borehole G16-22 between 71.45 m and 67.05 m below MSL a till was sampled at the base of a shallow north-east/south-west trending Saalian tongue-shaped basin. The till consists of a very poorly sorted, dark brown to dark greenish-brown diamicton of clay and sand together with a small amount of matrix-supported gravel with quartz, flint, limestone, sandstone and crystalline fragments (Sha et al, 1991; Van der Meer, 1992). The clay contains up to 20 % of particles <2 μm with c. 53 % smectite and c. 35 % illite. The calcium-carbonate content is 8 %.
Occasionally worn shell fragments are present. The organic matter content is <0.7 %. The heavy minerals are dominated by garnet (19 %), epidote (20 %) and hornblende (28 %) and also include a fair amount of volcanic minerals (Sha et al., 1991). Thin sections were made from three till samples (Mi 622, 623 and 624). They have been described as a part of

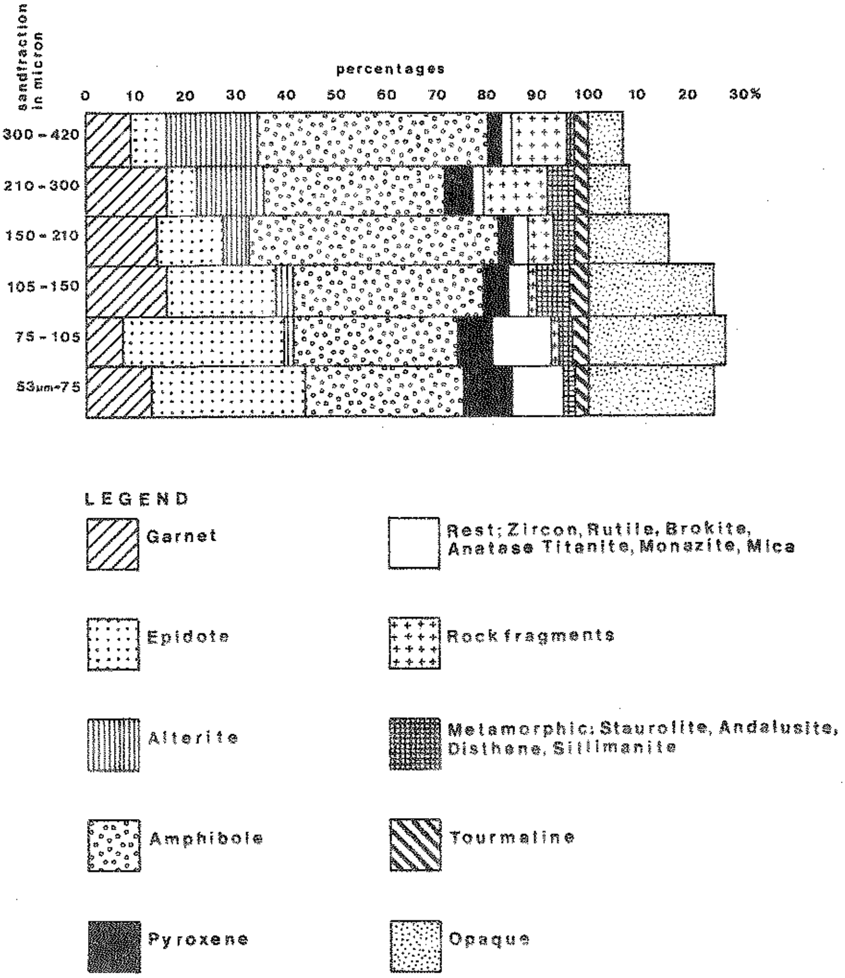


Fig. 45a. Heavy mineral diagram (fractionated) of borehole N935 (after Dijkmans, 1981).

a deformable bed with characteristics of wet-based glaciers resting on a sedimentary bed. The uppermost sample (Mi 622) has a lack of plasmic fabric and other strain markers such as brecciation. Similar features were noted in the other samples. The deposit may be interpreted as an ablation or flow till. According to Van der Meer (1992) the presence of microfossils in this sample suggests that deposition took place in a marine environment.
However, micropalaeontological analysis on the till samples did not support this suggestion. Marine fossils are absent except in the uppermost sample which contains a poor foraminiferal fauna with a significant amount of reworked components (Neele, 1991b).
SEM photographs of quartz grain surfaces revealed nail-shaped scratches and slickenside grooving which probably indicates deposition as a lodgement till (Sha et al., 1991).
The till contains material of Scandinavian provenance according to pollen analysis (Zag-

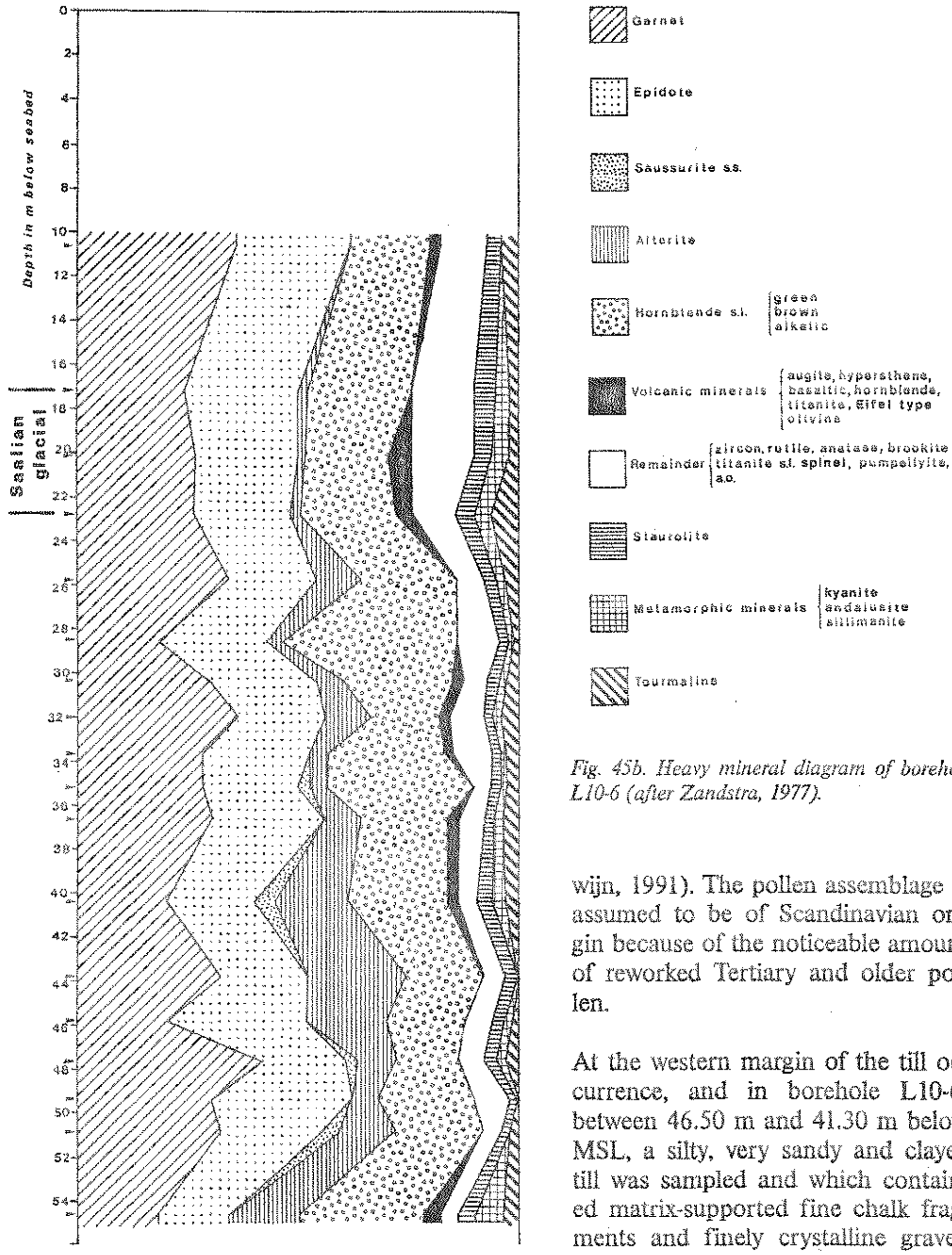


Fig. 45b. Heavy mineral diagram of borehole L10-6 (after Zandstra, 1977).

wijn, 1991). The pollen assemblage is assumed to be of Scandinavian origin because of the noticeable amount of reworked Tertiary and older pollen.

At the western margin of the till occurrence, and in borehole L10-6, between 46.50 m and 41.30 m below MSL, a silty, very sandy and clayey till was sampled and which contained matrix-supported fine chalk fragments and finely crystalline gravel. Towards the base the till is more sandy. Sediment-petrological analysis indicate that the gravel is of Scandinavian provenance, because it consists of flint, crystalline and chalk pebbles. The heavy mineral association (garnet, epidote-hornblende and about 4 % volcanic minerals without saussurite and alterite) also points to a Scandinavian origin (Fig. 45b). The percentage of glauconite is very low (Zandstra, 1977b). The pollen content

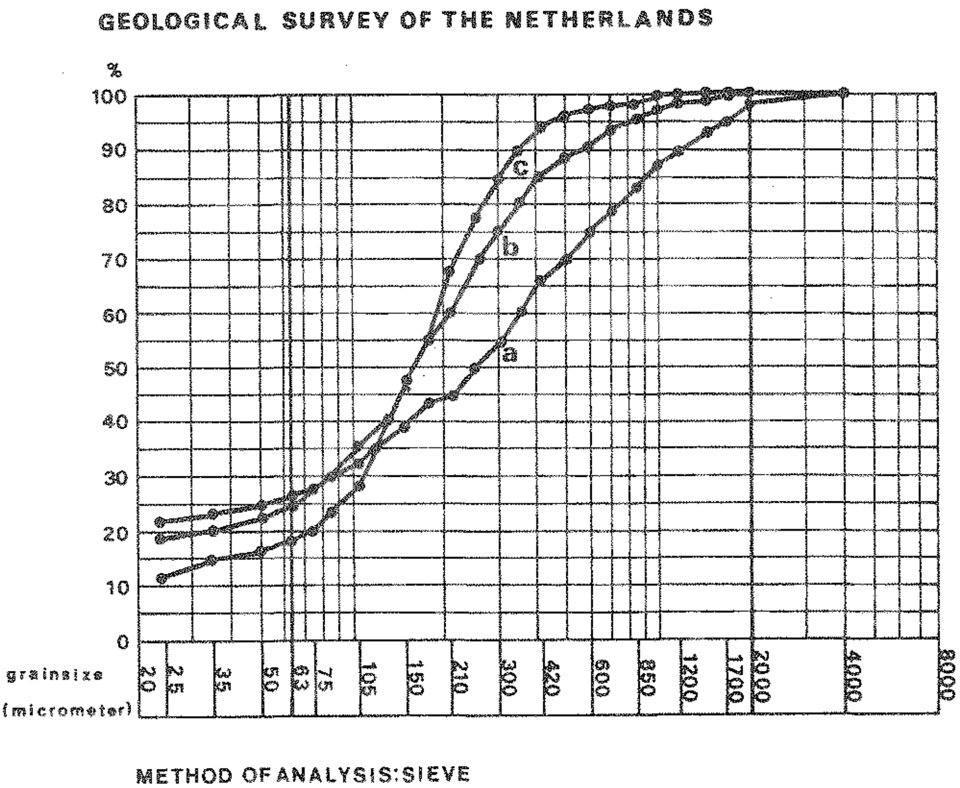


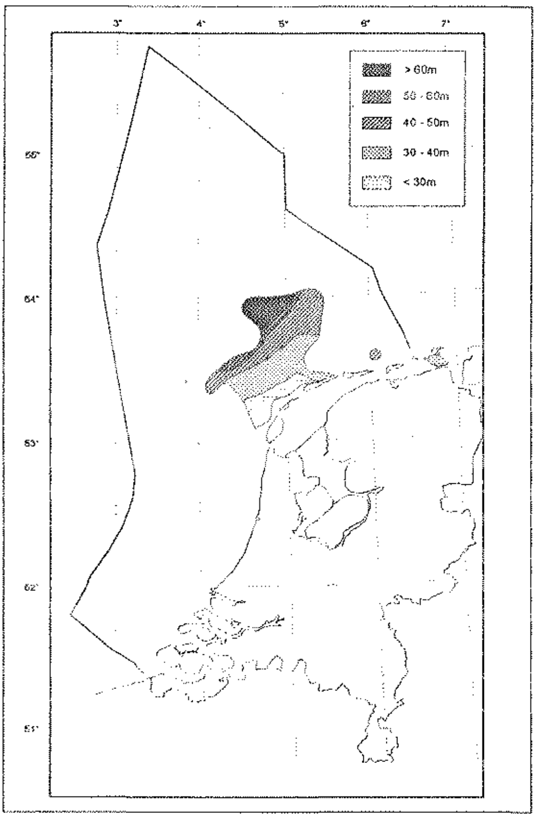
Fig. 46. Grain size distribution of the Borkumriff Formation in boreholes L15-56 (a), L15-65 (b) and L15-69 (c) west of the Island of Texel.

again consists of a high percentage of reworked material from Miocene and Pliocene deposits which are typical of Scandinavian glacial sediments (Zagwijn, 1977). North of this location in borehole L10-2 till was sampled between >52.80 m and 51.10 m below MSL.
In borehole L18-59 a similar deposit was sampled between >16.70 m and 16.58 m below MSL consisting of olive-grey sandy till without gravel below Weichselian periglacial sediments. Grain size analyses reveal a silt percentage of 16%; clay is absent. The sand fraction D10= 11.63 μm, D50= 274 μm, D90= 883.79 μm. No grains are present in the fraction of >1410 μm. The calcium carbonate content is very low: 0,3%.
In borehole L18-60 a sandy till without gravel was encountered to a depth of >16.33 m below MSL and directly below 0.66 m of Holocene marine sand. Grain size analyses show a silt percentage of 24.6, which is higher than in nearby borehole L18-59. The sand fraction D10= 7.32 μm, D50= 200.7 μm and D90= 739.9 μm. Grains are absent in the fraction >1190 μm. The calcium carbonate content is very low (0.2%). Grain size analysis of samples from boreholes L15-65, L18-74 and L15-56 are comparable with those of L18-60 and show similar curves. The calcium carbonate content however is much higher ranging respectively from 2.5, 3.0 to 6.6 % (Fig. 46).

Between the coast of the island of Texel to a position about 14 km to the west a till plateau is present which gradually dips westward from about 14 m to 26 m below MSL, with local hills and depressions (Sha et al., 1995). The till is non-calcareous. On the seismic profiles the till has a chaotic character (Sha et al., 1995).
No till has been sampled in the boreholes of blocks M1, 2, 3, 5, 6 and 8. Till was encountered in only two boreholes of blocks M7 (M7-46) and M9 (M9-11), while in some of the boreholes in these blocks gravel was sampled at the base of the Eem Formation. This probably indicates marine erosion of the till, or local non-deposition of till. The gravel in this case is thought to be an ice-contact deposit. In the adjoining Dutch Wadden Sea and the northern part of the province of Friesland the till is also absent or is present only locally in small patches. In this area the fluviatile Urk Formation (Holsteinian/Early Saalian) as well as the glaciolacustrine Peelo Formation (Elsterian) underlie the Holocene sediments (Van Staalduinen, 1977).
On the island of Terschelling the till forms a more or less continuous layer with a thickness ranging between about 1.50 m and 4 m.

Tills are also found in several boreholes in the coastal area in the German sector of the North Sea. The tills are grey to greyish-green with medium- and coarse-grained sand enclosures. The tills are present at depths of 20 m just near the north German coast to >60 m below MSL in the area between 54°N and 55°N/6E and 7°E. The till is overlain by a sequence of Eemian marine, Weichselian periglacial and Holocene marine deposits (Sindowski (1970). The till sample from the German borehole 20 contained only 80 cobbles of gravel, insufficient for provenance studies. Because of the absence of rhomb-porphyries and rapakivi, Sindowski (1970) has assumed that in the German sector the till was deposited during the Drenthe Glacial Stage.

Fig. 47. The geometry and depth of the Borkumriff Formation in metres below MSL.



The tills in the Dutch sector of the North Sea although forming a rather discontinuous sheet with the tills on land were most likely deposited during the same phase.
Oele (1971) has suggested that, based on data from high resolution seismic profiles, the till which is present on land in the western Netherlands, locally continues into the North Sea. However in none of the boreholes in the glaciated area west of the Dutch coast has till yet been encountered.
Fig. 47 shows the geometry and depth of the top of the formation below MSL.

5.5.2 The Netherlands

The Saalian till of the northern Netherlands is present as a sheet at or near the surface and with a thickness ranging from 1 m to 5 m. The till is referred to the Drente Formation (Ter Wee, 1962) and is regarded as having been deposited during the Drente ice advance. In the northern Netherlands only one till sequence can be distinguished and it is assumed to have been deposited by one uninterrupted ice cover (Rappol, 1987). In a petrographic till classification (Hesemann-method) based on the dominant source area of indicator pebbles, Zandstra (1983a) distinguishes 4 till groups derived from 10 different source areas which are grouped together into four main source areas: I) East-Baltic, II) East-central Baltic and West-central Baltic, III) South Baltic and IV) South Norway (Oslo area) (Fig. 31).

Till on the Island of Texel contains pebble indicators which originate mainly from area III but partly from area II.

In the western part of The Netherlands tills of the Drente Formation (Dr6) are mainly present in and between the tongue-shaped basins. They are overlain by Eemian marine, Weichselian periglacial and Holocene marine sediments. The top of the till between the basins lies between about 30 m and 40 m below NAP and thicknesses of up to 15 m are found. In the Amsterdam Glacial Basin is till found at a depth of about 55 m below NAP (De Gans, 1991; De Gans et al., 1987) and in the tongue-shaped basin at the coast near Wijk aan Zee the top of the till occurs at a depth of 105 m below NAP (Westerhoff et al., 1987). In the glacial basins thicknesses of up to 6 m are found. Pebble indicators point to a South Swedish (Småland and Bornholm) origin (area III) (Zandstra, 1987). However tills from the former island of Wieringen also contain pebbles from area I. There are no analyses available on till samples from the Dutch part of the Waddenzee.

Comparisons with the heavy mineral content of tills in the northern Netherlands have not been made because analyses are available only for three North Sea till samples.

5.6 Marine Saalian deposits in the Dutch sector?

In borehole G16-22 below the Saalian till another till is present between 149 m and 139 m below MSL (discussed in Chapter 4). This till shows the same pollen assemblage as the upper till. Van der Meer (1992) found no lithological and microstructural differences between the two tills. Zagwijn (1991) and De Jong (1991) suggest in their reports that the two tills, as well as the intermediate marine sediments, belong to the Saalian glaciation. This view is supported by the fact that the marine sediments between the tills have been deposited in an environment in which marine boreal to probable low-arctic conditions prevailed (Meijer, 1991). The dominant mollusc species are *Arctica islandica, Cerastoderma edule, Spisula elliptica, Macoma balthica* and *Macoma calcarea*. A post-Holsteinian age is deduced from the presence of *Chamelea gallina striatula, Angulus donacinus/distortus* and *Pholas dactylus* (Meijer, 1991). The dominating foraminifera species are *Ammonia beccarii, Elphidium excavatum f. clavata, Nonion orbiculare* and *Elphidium asklundi* which indicate arctic to arctic-boreal conditions in a shallow, sub-littoral marine environment (Neele, 1991b).
If the suggestion put forward by Zagwijn (1991) and De Jong (1991) for a Saalian age of the marine sediments is correct, it implies that this is the first find of Saalian marine deposits in the Dutch sector of the North Sea. This view is further supported by the interpretation given to the mollusc association by Meijer (1991) for a post-Holsteinian fauna. The

till above the marine deposits is correlated with the till of the Drenthe Glacial Stage. The evidence for the presence of only one Saalian till sequence is sufficiently great to indicate that the lower till is not Saalian but Elsterian in age. This leads to the conclusion that the marine deposits were probably deposited during an interstadial preceding the Drenthe Glacial Stage.

In Schöningen (northern Germany) recently, probable Saalian, Reinsdorf Interglacial Stage has been described in which there is a very pronounced warm period (Urban, 1995). It is possible that the sea-level rise related to this interglacial is reflected by the tide-dominated glaciomarine sediments sampled in borehole G16-22 and that these also belong to the Reinsdorf Interglacial.

North of Borehole G16-22, in the Danish sector, in borehole 89/7a between >106.80 m and 100 m below MSL Saalian, glaciomarine deposits were also sampled overlain by Eemian marine sediments (Thompson et al., 1992).

Dating of molluscs by means of the amino-acid method could possibly give age determinations of marine Saalian deposits.

5.7 Glacial gravels (Indefatigable Grounds Formation)

5.7.1 Dutch sector

Concentrations of gravel are present at several locations near or at sea bed (Pratje, 1951; Valentin, 1957; Veenstra, 1969). These gravel deposits are partly reworked by the Eemian and Holocene transgressions and are regarded as ice contact deposits. The sediments are referred to the Indefatigable Grounds Formation. This formation is named after gravel deposits found on the sea bed at the Indefatigable Grounds south-west of the Dogger Bank (Harrison et al., 1987). Because of the limited areas in which gravel is present on the sea floor and the fact that most of the gravel has been reworked during the respective Eemian and\or Holocene marine transgressions, both the Weichselian and Saalian deposits are grouped together as the Indefatigable Grounds Formation.

Pratje (1951) mapped gravel occurrences on the sea bed from fishery charts. He distinguished three main areas notably north-west of the island of Texel, the Borkum Riff Grund and an extensive area west of the Danish coast. He regarded the gravel as being deposited during the Saalian glaciation.
At some locations in the southern G blocks and northern N blocks gravel concentrations are present at or near the sea bed surface. They contain blocks of red Triassic sandstone (Buntsandstein) (Bergman, 1991) which were probably entrained by the Saalian glaciers from Heligoland (Schmidt-Thomé, 1982). In addition a silty sandstone with marcasite crystals was collected. Ostracod analyses revealed a Jurassic (Late Portlandian) age. This rock fragment was probably derived from northern Germany or is from the Baltic area (Lissenberg, 1995). The occurrence of these rocks may indicate a westerly transport direction of the ice during the advance.
The gravel in the eastern G blocks of the Dutch sector is closely associated with the presence of the so-called Borkum Riff Grund in the western German sector. This relatively 'high' area possibly forms the continuation of the Oldenburg-East Frisian Geest (Figge, 1983). On the basis of gravel analysis, Bäsemann (1979) concluded that the Borkum Riff-

grund was formed during the Older Saalian glaciation. The gravel deposits in the eastern part of the G blocks also overlie Holocene sediments and were probably transported westward during the Early Holocene.

A location where a more extensive gravel deposit is present lies to the north-west of the island of Texel in blocks L14 and L15. On fishery maps the gravel field is shown as much larger than is really the case. Moreover, the original extent of the gravel has probably been enlarged by trawling which has, in effect, spread the material over a wide area of the sea bed. The gravel percentages range between <2% to 77,4%. The average thickness of the gravel layer is 0.20 m. The gravel locally overlies till, but predominantly it covers the periglacial sediments of the Tea Kettle Hole Formation. Locally the formation is overlain by Holocene marine sediments. The grain size of the sand fraction of the deposit is much higher than the surrounding Holocene deposits and has an average D50 value of 310 μm (Van der Klugt, 1991).

In block L10 north of the till deposit encountered in borehole L10-6, borehole L10-2 recorded between 49.15 m and 47.50 m below MSL a gravel layer with crystalline fragments overlying Saalian till. A similar sequence was sampled in borehole M4-4 between 42.60 m and 41.60 m below MSL. In block N12 borehole N12-1 recorded a gravelly sandy layer again overlying till present between 18.82 m and 15.92 m below MSL.

For determination of the provenance of the gravel by the Hesemann-method insufficient fine crystalline components have been sampled. Burger (1994) carried out some determinations on four gravel samples from the blocks L14 and L15. Based on the presence of crystalline material, together with Ordovician chalk, the determination was 7.3% to 12.3% flint and 0% to 12% quartz in the fraction 3 mm to 5 mm, and 15.9% to 37.7% flint and 4% to 7% quartz in the fraction 5 to 20 mm. He concluded that the gravel is of Scandinavian provenance and most probably belongs to the Heerenveen Group of Zandstra (1983a and b). The Heerenveen Group originates from the West-Baltic, Dalarne and South Sweden and was deposited during the Middle Swedish iceflow (Rappol et al., 1989). Fig. 48 shows the occurrences of gravel deposits. In borehole L17-2, about 40 km west of the Dutch coast, and at 30.40 m below MSL gravel was sampled under Holocene marine sediments. Gra-

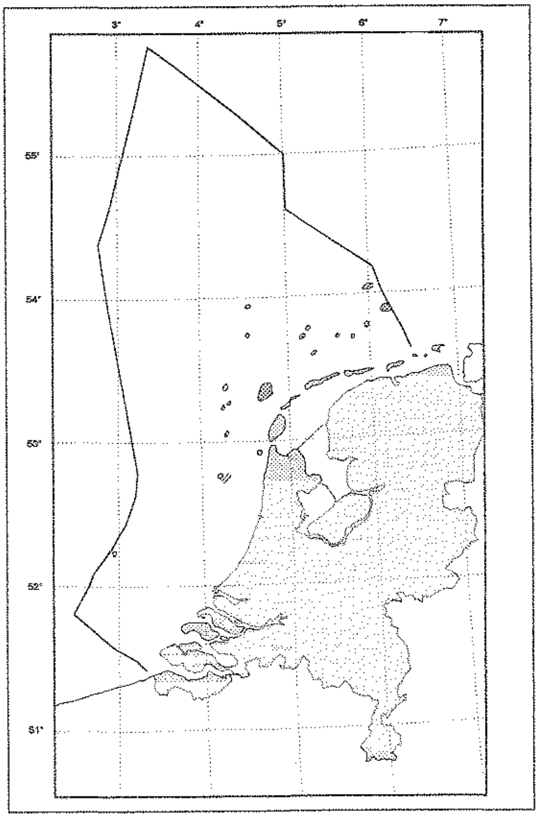


Fig. 48. Map showing locations of boreholes with Saalian gravels. The larger areas shown contain gravel on or near sea bed. The parallel lines indicate the location of the eskerlike feature recorded in block Q4.

vel analysis revealed components which differ from the known Scandinavian types. It is concluded therefore that their provenance is possibly from West Norway and that the gravel is derived from the sea bed between Norway and the Dutch coast (Zandstra, 1969b).
South-west of Texel, at the northern end of the Molengat,during the inspection of a historical wreck divers reported the presence of blocks of > 1 m in diametre on the sea bed (Maarleveld, pers. comm).

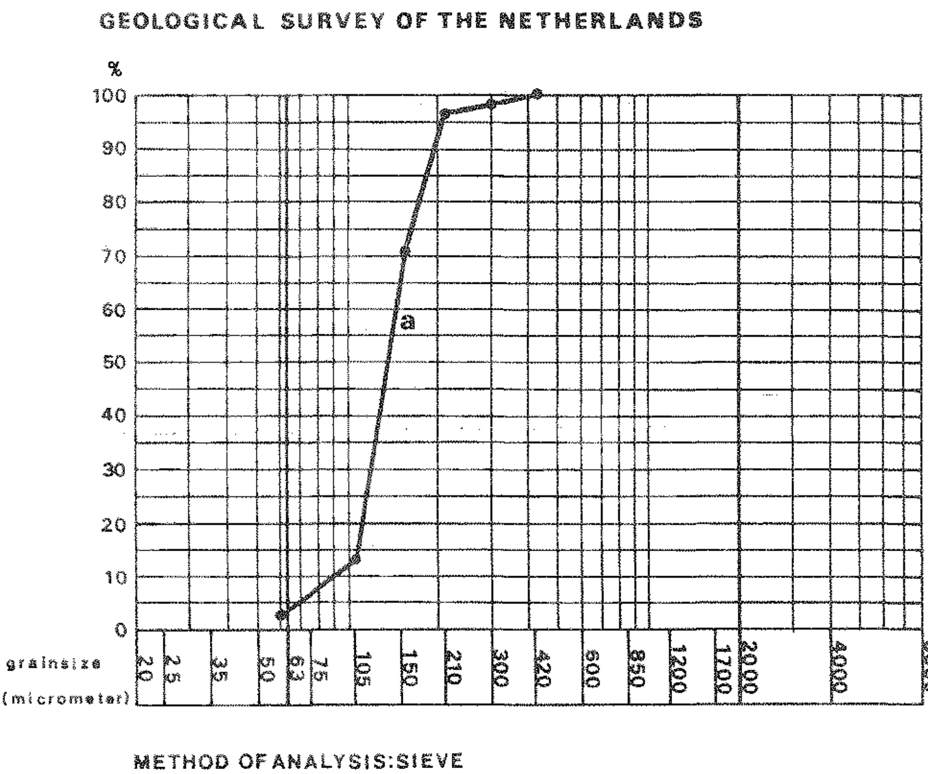
5.8 Fluvioglacial sediments (Molengat Formation)

5.8.1 Dutch sector

The Molengat Formation has been sampled at some localities along the line of the maximum extent of the Saalian ice sheet. The formation was named after the Molengat, a tidal channel south-west of the island of Texel.

In borehole L18-95, drilled in a shallow channel south of the till plateau (see Chapter 5.5), between >25.64 m and 22.24 m below MSL the Molengat Formation consists of fine- to medium-grained, calcareous, micaceous sand. The grain size distribution is bimodal with

Fig. 49. Grain size anlysis of the Molengat Formation in borehole F3-2 (a).



the higher percentages between 105-210 μm and 300-450 μm. The deposits are overlain Saalian sediments that were slightly reworked during the Eemian and/or Holocene transgressions. In borehole F3-2 the formation, sampled between 56 m and 49.50 m below MSL, consists of very fine, slightly calcareous sand (Fig. 49). The sediments rest on the Cleaver Bank Formation and are overlain by the Eem Formation.
The deposits were sampled west of the maximum extent of the ice sheet in the German sector. Because of the occurrence of ice-proximal deposits it is assumed that the maximum extent was further west than suggested by Cameron at al. (1993).
In borehole F17-5 drilled at the northern end of a subglacial valley between 79.10 m and 76.05 m below MSL, a fine grey sand was sampled with an increasing percentage of silt towards the base. The deposit is underlain by the Cleaver Bank Formation and overlain by Eemian marine sediments.
Borehole G11-1 consists between 44 m and 39.95 m below MSL, of fine to medium gravelly sand overlying the Cleaver Bank Formation. The grain size ranges from a mean value of 150 μm to 375 μm. The sand is free of $CaCO_3$. In the eastern part of the Dutch sector and in the mouth of the Ems estuary, in borehole N9-36 between >22.40 m and 16.40 m below MSL, medium sand was sampled with some gravel overlying very fine, micaceous sand. The sand layers are free of $CaCO_3$. The underlying till, sampled in boreholes close to the above location, was not reached in borehole N9-36. Near this location several other boreholes have been drilled and in all cases fluvioglacial sand deposits were encountered.
Fluvioglacial sand below the till was sampled in only one borehole. In borehole L10-6 between 49.75 m and 46.43 m below MSL fine- to coarse-grained sand with fine gravel was proved. The heavy mineral content of this deposit is identical to that of the overlying till (i.e. garnet, epidote and hornblende). The gravel is of Scandinavian provenance with a high percentage of chalk (Zandstra, 1977a).

Because the fluvioglacial deposits have not been covered by till or glaciolacustrine clay, they were not protected against erosion during the Eemian transgression. Consequently, during this transgression most of the sediments were reworked and redeposited as marine deposits containing shells.

5.8.2 The Netherlands

In The Netherlands fluvioglacial deposits of the Molengat Formation consist mainly of sand or gravelly sand derived from local reworking of older sediments. In some cases they hardly contain any Scandinavian material (Zandstra, 1983b). The sediments are referred to the Drente Formation.

5.9 Reworked Saalian fluvioglacial deposits

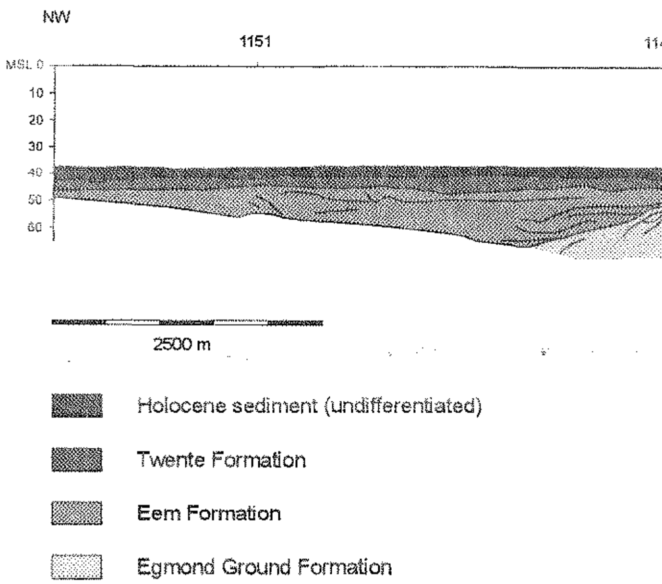
In the glaciated area and in a broad zone around the maximum ice-limit, the Eem Formation often contains a small percentage of gravel which is probably derived from Saalian sandr and other fluvioglacial deposits. Within this area numerous boreholes have been drilled into the Eem Formation some of which are discussed below.
In borehole K17-2 fine sand with gravel and containing marine molluscs has been sampled between 21.50 m and 15.50 m below MSL. The sand overlies the periglacial Tea Kettle Hole Formation and underlies the Late Eemian-Early Weichselian Brown Bank Formation. The heavy mineral assemblage includes a high percentage of garnet, epidote and hornblende, but that of alterite is low (Zandstra, 1969a). Borehole K18-11 between 35.40 m and

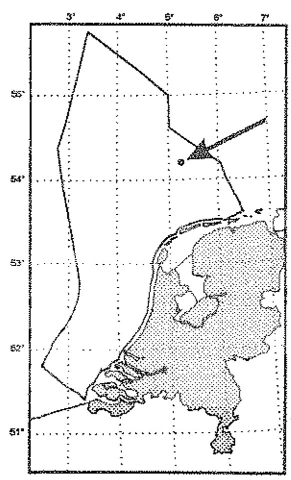
>32.40 m below MSL contains very fine- to fine-grained sand with a marine mollusc association and fine gravel and is overlain by periglacial sediments of the Weichselian Twente Formation. In borehole G18-2 between 64.50 m and 50.05 m below MSL fine- to medium-grained sand with marine molluscs and locally with gravel was sampled and is overlain by the Twente Formation.
Borehole F16-5 between >57.60 m and >55.60 m below MSL contains fine sand with fine to coarse gravel and marine molluscs. The heavy mineral content is rich in garnet, whereas the gravel consists largely of flint, as well as crystalline and chalk pebbles of Scandinavian origin (Zandstra, 1974).
Sediment-petrological analysis of sediments of the Eem Formation in borehole K17-2, between 50.50 m and 46.20 m below MSL and located near the former Saalian ice-limit, record the presence of gravel of Scandinavian origin (type FG VII) (Zandstra, 1969a).

5.10 Saalian tongue-shaped basins

Within the area of maximum extent of the Saalian ice sheet the presence of two basins can be deduced from a dense pattern of high resolution 3.5 kHz seismic lines. A shallow, over 20 km long, south-west/north-east trending valley is present in blocks G13, G16 and L3. At the northern end the base of the valley was reached at 65 m below MSL. At the southern end of this valley borehole G16-22 was drilled and a lodgement till was sampled between 71.45 m and 67.05 m below MSL (see Chapter 5.5). The till is evidence for the

Fig. 50. Interpretation of NW-SE running seismic profile through the northern part of the Saalian tongue-shaped basin in block G16 containing an Eemian infill and showing deformation structures in the Egmond Ground Formation. The basin is overlain by the Twente Formation and Holocene sediments.





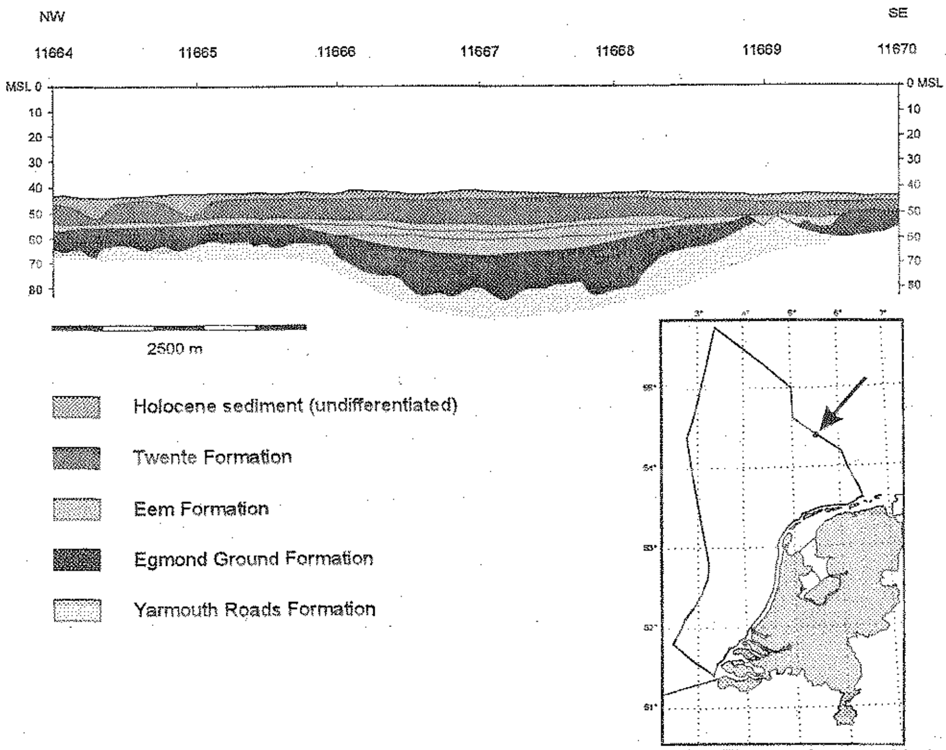


Fig. 51. Interpretation of a NW-SE running seismic profile through a probably Elsterian basin in block G10 showing icepushed Lower Pleistocene deposits of the Yarmouth Roads Fm. The basin is filled with the Egmond Ground Fm and Eem Fm. The Twente Fm and Holocene sediments overlie the basin.

presence of ice in this valley. The ice probably filled a pre-existing valley during the Elsterian glaciation which became partly filled with Holsteinian or marine Saalian sediments. The Saalian basal till in the valley is overlain by Eemian marine sediments (Sha et al., 1991; De Wolf, 1991). In the centre of block G16, and at the eastern side of the same valley, steeply dipping reflectors have been observed on the seismic profile indicating deformation of the Holsteinian marine sediments of the Egmond Ground Formation by ice-pushing (Fig. 50).

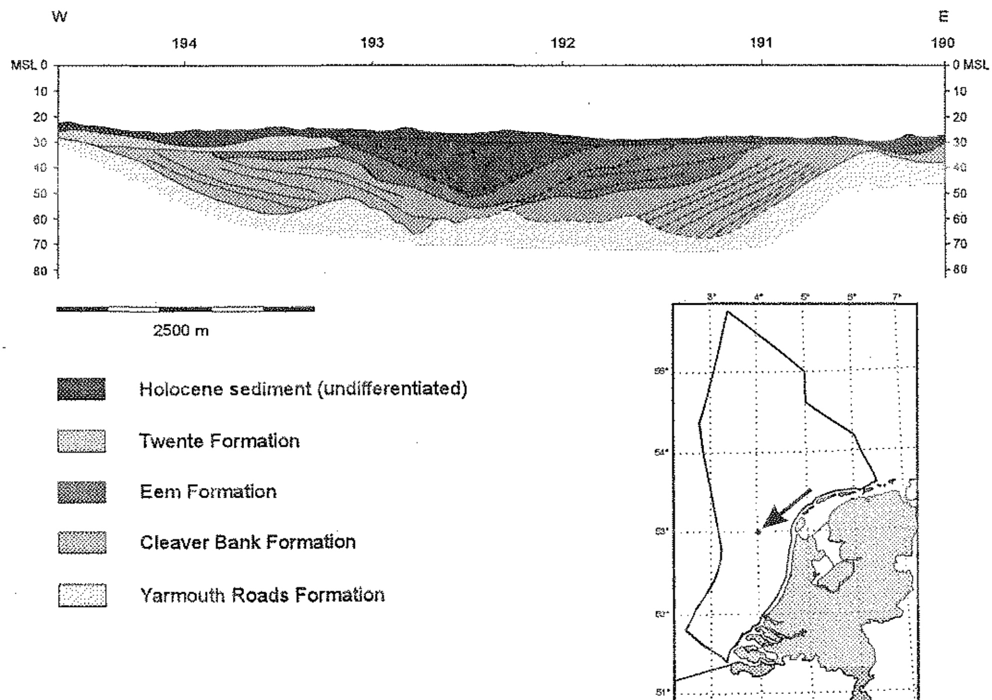
In block G10 north of this valley, another valley, 83 m below MSL deep, can be recognised on the high resolution seismic profiles. This valley has an irregular base and seismic interpretation indicates it is filled with Holsteinian (or Saalian marine) and Eemian marine sediments. The valleys are probably interconnected. Along the eastern margin of the valley in block G10 Lower Pleistocene sediments are present in the very elevated position of only 8 m below the sea bed (50 m below MSL). Probably these sediments were ice-pushed during the Elsterian or Saalian ice-advance, whereas the southern extension of this basin was apparently filled again with ice during the Saalian (Fig. 51).

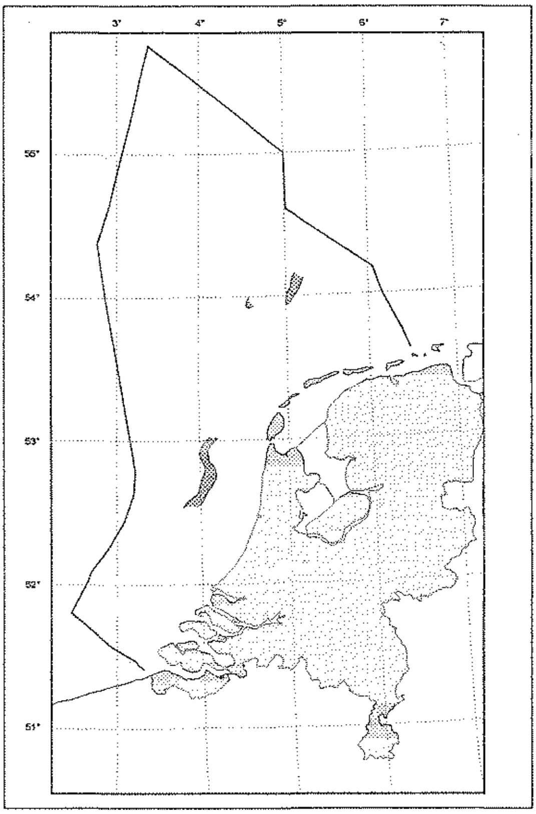
In block L2 in borehole L2-1 the upper surface of the till was sampled at a depth of 68 m below MSL which is about 20 m deeper than the depth of the top of the till in surrounding boreholes. On the high resolution seismic profiles no valley is evident but possibly a small tongue-shaped basin is present at this location.

A second, more extensive, basin is present off the Dutch west coast. Here a 5 to 10 km wide north-east/south-west trending valley has been mapped between about 52° 30'N and 53° 05'N and more or less along 4° E longitude (Oele, 1971; Oele & Schüttenhelm, 1979). Because of the thickening of the Holocene deposits the southern end of the valley is only just visible on the high resolution seismic profiles.

The maximum depth to the base of the valley ranges from about 30 m to 40 m below the sea bed (between about 61 m to 66 m below MSL). On the seismic profiles deformation structures caused by ice-pushing can be observed along both margins of the valley, evidence suggesting that the valley was once filled with ice. The sedimentary infill of the valley dates from the Saalian, Eemian, Weichselian and Holocene stages. On the high resolution seismic profiles the lower part of the infill, which shows westward and eastward prograding reflectors, is probably Saalian in age (Fig. 52). In the valley only one deep borehole and one CPT (Cone Penetration Test) is sited. CPT P3-40 is located in the centre of the valley and probably reached the fluvioglacial deposits near the base at 29.70 m (56.15 m below MSL). The upper 3.50 m of the infill probably consists of sandy Holocene marine sediments. These overlie a sequence of laminated deposits down to 13.70 m below sea bed probably deposited during the Eemian. Between 29.70 m and 13.70 m below sea bed a slightly silty clay layer is present (estimated shear strength of c. 90 to c. 120 kN/m^2). In the northern part of the valley a number of boreholes were drilled penetrating Eemian marine sediments (Eem Formation), e.g. in boreholes P3-24 and 26. Late Eemian/Early Weichselian clay deposits (Brown Bank Formation) were sampled in boreholes K18-16, 21, 23 and

Fig. 52. Interpretation of a seismic profile through a Saalian tongue-shaped basin showing prograding reflectors within the Cleaver Bank Fm. The post-Saalian infill consists of the Eem Fm and Holocene sediments.





24 with the top of the clay lying at only 1 to 2 m below the sea bed. On the eastern margin of the valley in block P3 periglacial sediments of the Weichselian Twente Formation overlying the Eem Formation were sampled in boreholes P3-27 and P3-28.
In borehole P3-51 the Eem Formation was sampled between >40.30 m and 28.30 m below MSL and consists of marine sand with clay laminae towards the base.
Borehole Q1-93 was drilled in block Q1 close to the eastern margin of the valley. In this borehole the following sequence is recorded:

Fig. 53. Distribution of Saalian tongue-shaped basins in the Dutch sector of the North Sea.

(Depth below sea bed)

- 0.00 m to 4.00 m Holocene marine sand
- 4.00 m to 9.60 m Weichselian periglacial sand
- 9.60 m to 10.80 m Eemian marine sand
- 10.80 m to 24.00 m Saalian periglacial sand
- 24.00 m to 32.00 m Holsteinian marine sand
- 32.00 m to >72.00 m Cromerian fluviatile sand

The Eemian and Weichselian deposits overlie the eastern shoulder of the valley while the valley is incised in pre-Eemian sediments.
Another possible way in which this valley might have formed is that originally an ice-margin valley developed which subsequently became infilled with ice during a further advance of the ice sheet in a westerly direction. The presence of Holsteinian sediments in borehole Q1-93 disproves the suggestion by Oele & Schüttenhelm (1979) that the valley was Elsterian in age. Fig. 53 shows the distribution of the basins.

This basin probably forms the continuation of north-east/south-west trending basins present in the subsurface of the western Netherlands. For example, in the province of North Holland a number of such basins have been mapped, and which decrease in width from about 15 km below Amsterdam to about 7 km near the coast. The basal infill of the

onshore basins consist of fluvioglacial sand locally overlain by more than 40 m of glaciolacustrine clay. The depth of the basins are about 120 m below NAP (De Gans, 1991; De Gans et al., 1987).

Oele (1971) tentatively suggested a connection between the above basin in the P and Q blocks with a specific onshore valley near Egmond. High resolution seismic profiles recently obtained from the area between the coast and the offshore basin, showed that although a valley continues offshore, its genesis is probably not glacial and therefore a connection between the two valleys seems unlikely.

5.11 Deformation structures

Deformation structures due to ice-pushing during the Saalian glaciation, and interpreted as such on the high resolution seismic profiles, are mainly found in the south-western area in which the ice sheet extended. Furthermore they are locally present along the tongue-shaped basin in the southern G and F blocks and also along the basin occurring further south. At several locations south-east of the basin in the G and F blocks steeply dipping reflectors are seen on the high resolution seismic profiles indicating ice-pushing of Lower Pleistocene fluviatile sediments (blocks Q 4, 5 6 and 7). The structures are present just below sea bed at depths of between 41 m and 24 m below MSL. As high resolution seismic profiles with deep penetration are not available for this area, it is not possible to map the deformed structures and ice-pushed ridges in detail and also to trace the intervening basins which are probably present.

In several boreholes ice-pushed formations have been sampled close to the sea bed. In borehole Q4-44 at a depth of only 9.50 m below sea bed (35.20 m below MSL) Lower Pleistocene fine, silty, locally clayey, sand has been sampled (Yarmouth Roads Formation). In borehole Q5-24 at a depth of 26 m below MSL (9 m below sea bed) Lower-Pleistocene non-marine, very fine- to fine-grained sand, with clay laminae, and calcium carbonate free was sampled. The deposits are overlain by Eemian and Holocene marine sediments (Spaink, 1972). Deformation structures were observed in the periglacial sediments of the Tea Kettle Hole Formation west of the island of Texel (see Chapter 5.2).

In block P15 south and west dipping reflectors were observed on seismic profiles. They are probably formed by frontal ice-pushing, which resulted in the formation of a small ridge. On top of the ridge borehole P15-36 was drilled. In this boreholethe Lower-Pleistocene laminated silty clay forming the fluviatile deposits of the Winterton Shoal Formation were sampled at a depth of 10.60 m below sea bed (35.60 m below MSL). Pollen analysis showed that Lower Pleistocene Cromerian Interglacial I sediments overlie deposits of Waalian age (De Jong, pers. comm.). No glacial deposits were found. This indicates either an advance of the ice which was so short-lived that no morainic deposits of any importance were left behind or the deposits were less resistant against erosion and as a result, during the more powerful Eemian transgression, the morainic material was subsequently eroded. Seismic profiles did not show the presence of an associated small tongue-shaped basin north of the ridge as one might have expected.

Oele (1971) recognized deformation structures on high resolution seismic profiles in blocks Q4 and Q5 and in blocks P7 and P10. He suggested that they were the result of Saalian ice-pushing. New data has provided evidence that the Saalian ice sheet did not

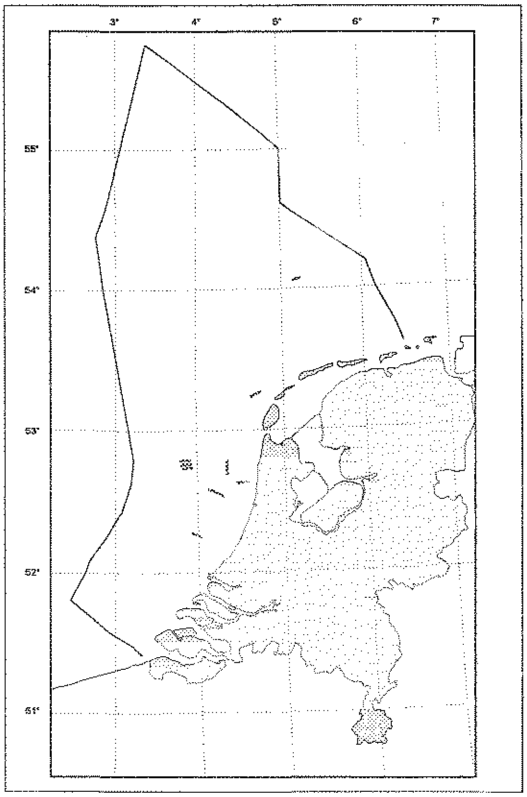


Fig. 54. Map showing locations of deformation structures due to Saalian ice-pushing recorded in the Dutch sector of the North Sea.

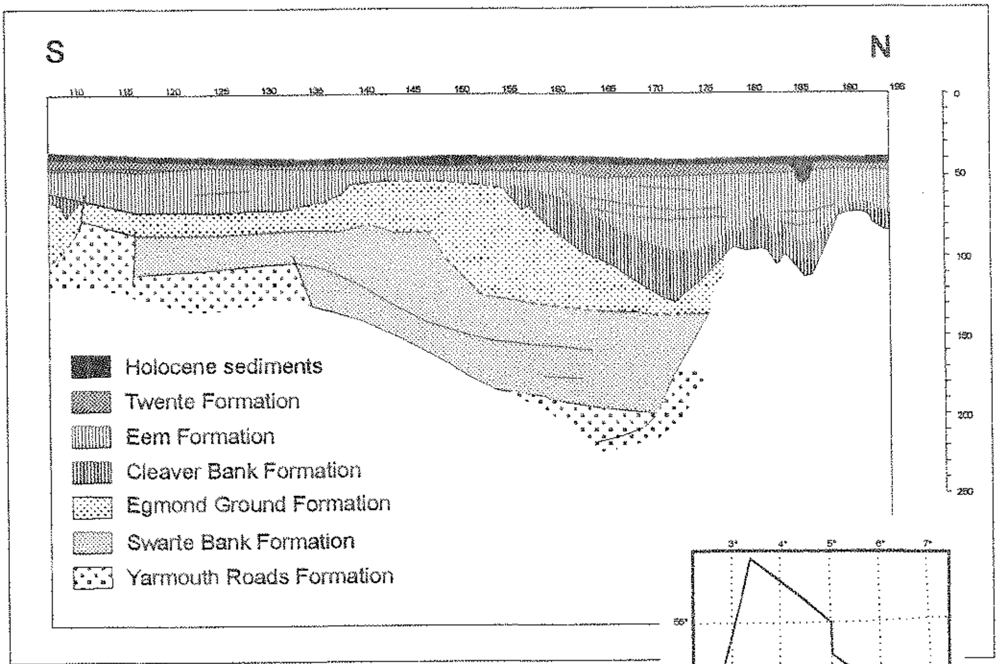
reach as far as these blocks and that the Elsterian ice sheet must have been responsible for the deformation (see Chapter 4) (Fig. 54).

In The Netherlands a broad zone of ice-pushed ridges is present along the flanks of the tongue-shaped basins. In the central part elevations of >100 m are present locally, while in the western Netherlands the ridges are much lower and buried by Late Pleistocene and Holocene sediments.

5.12 Subglacial valleys

In block F18 and in blocks L2, 3, 6 and 9, two north-south trending valleys are present according to the interpretation of the high resolution 3.5 kHz seismic profiles. They have maximum depths ranging from 30 m to 80 m below sea bed (>60 m to 128 m below MSL). They are from rather less than 2 km up to 6 km in width and have a maximum length of 55 km. The bases of the valleys are not always visible on seismic profiles. Both valleys are incised into Holsteinian sediments and filled with Eemian marine sediments. Glaciolacustrine deposits of the Clearer Bank Formation are only locally present in this area.
Borehole F17-5 was drilled at the northern end of one of these valleys and recorded between 80.20 m and 77.10 m below MSL a glaciolacustrine deposit with material of Scandinavian provenance (Zagwijn, 1971c). The glaciolacustrine sediment is overlain by Saalian fluvioglacial and Eemian marine sediments.

In the north-western part of the glaciated area a number of small north-west to south-east trending valleys can be seen on high resolution seismic profiles (Kok & Mesdag, 1982; Joon et al., 1990) (Figs. 55 and 56). The valleys vary in width between 1 km and 4 km, their bases are very irregular and vary considerably in depth, especially along the axis and range from 50 m to 91 m below MSL. These figures are comparable with the profile observed along the axis of the Elsterian valley (Chapter 4).
Mapping of these valleys with high resolution seismic methods is problematical because of the limitations of penetration depth of the seismic systems mentioned in Chapter 2. During the seismic survey low frequency systems have also been used which in the upper layers have the disadvantages mentioned in Chapter 2. The valleys which are recorded in blocks L7 and L8 have been mapped with a 9-element sparker system. As a result the lower part of the valleys is only partly visible.



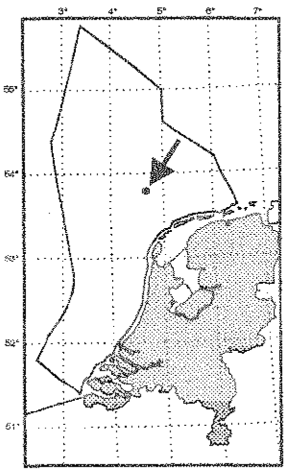


Fig. 55. Interpretation of seismic profile through Elsterian and Saalian subglacial valleys in the northern L-blocks (after Kok & Mesdag, 1982).

In the Central North Sea between 56°N and 59°N and incised more than 100 m below the sea bed, mainly north-east/south-west trending Late Saalian valleys are present (Holmes, 1977; Caston, 1977; Wingfield, 1989). According to Wingfield (1989) unequivocal discharge directions are lacking. From the pattern of valleys no conclusion can be drawn about the position of the ice sheet.

Comparable Saalian subglacial valleys have been found in the eastern Netherlands (Van de Meene, pers. comm.). In northern Germany the Saalian valley of the 'Nordfriesische Rinne' with its tributaries and the Saalian valleys in the Eider-SorgeTreene district are, according to Behre et al. (1979), filled with Eemian marine sediments like the valleys in the Dutch sector of the North Sea. In the North Sea during the Eemian transgression the former Saalian surface was drowned rapidly. According to the continuous GRIP Summit $\delta^{18}O$ record (Johnsen, et al., 1992; Dansgaard et al., 1993a, 1993b) the transition from cold to warm stage can take place in a relatively short period of time. The transition of the Weichselian Stage to the Holocene Stage took only 50 years while in 30 years the dust which is present in the Weichselian ice cores, disappeared due to increasing precipitation.

5.13 Esker-like features

At a location close to the western margin of block Q5 (52° 43'N/4° 21'E) gravel was recorded in the superficial sediments of one of the cores (Schüttenhelm, 1980). This gravel de-

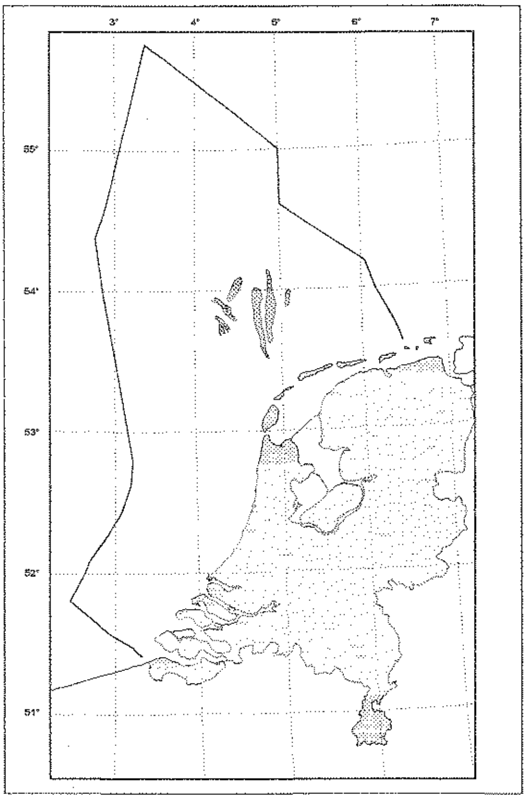


Fig. 56. The distribution of Saalian subglacial valleys in the Dutch sector of the North Sea.

posit was traversed during trenching for the pipeline between the wellhead in block Q1 and landfall near IJmuiden. According to the trenching report a gravel layer several hundreds of metres width was trenched at this location. A high resolution seismic profile along the axis of the pipeline route and several cores were taken during a pre-trench survey. Surprisingly the presence of gravel was not revealed by this survey and it is concluded that the deposit was a narrow band probably belonging to a north-west/south-east trending esker-like and deposited during the Saalian glaciation.

Several fragments of gravel and some boulders were collected and submitted to the Geological Survey. Most fragments appear to be ventifacts faceted by the abrasive effect of wind-blown sand. This tends to indicate that at least part of the sand was blown out during the Weichselian stadials probably lowering the esker-like feature and at the same time enriching the gravel content. In borehole Q4-49, close to the pipeline route, and at a depth of 4 m to 1 m below the sea bed, fine to medium gravelly sand was sampled containing, amongst others, quartz, flint and crystalline pebbles. The sand probably overlies ice-pushed Lower Pleistocene fluviatile deposits because of the elevated position of the sediments. The seismic profile shows a ridge-like structure possibly caused by the occurrence of gravel (Fig. 57).

In blocks Q7 and Q8, Oele (1971) on high resolution seismic profiles observed the presence of isolated mounds consisting of very stiff material and occurring at depths of about 30 m below MSL. He interpreted these mounds as elevations of boulder clay. These reflectors may, in fact, indicate eskers. On high resolution seismic profiles of blocks L6, M1 and F18 also esker-like features have been described (Koomen, 1993).

5.14 A British ice sheet in the southern North Sea?

In many previous publications the line indicating the maximum ice-limit of the Saalian glaciation is shown crossing the North Sea from the Dutch coast south of Haarlem through the southern Bight of the North Sea towards eastern England. This line has been drawn for decades without either any offshore evidence in the North Sea or any onshore evidence in Britain (Woldstedt, 1929; Tesch, 1942; Flint, 1971; Redding, 1976; Nilsson, 1983; Rose, 1987). In the absence of any better evidence, Oele & Schüttenhelm (1979) tentatively con-

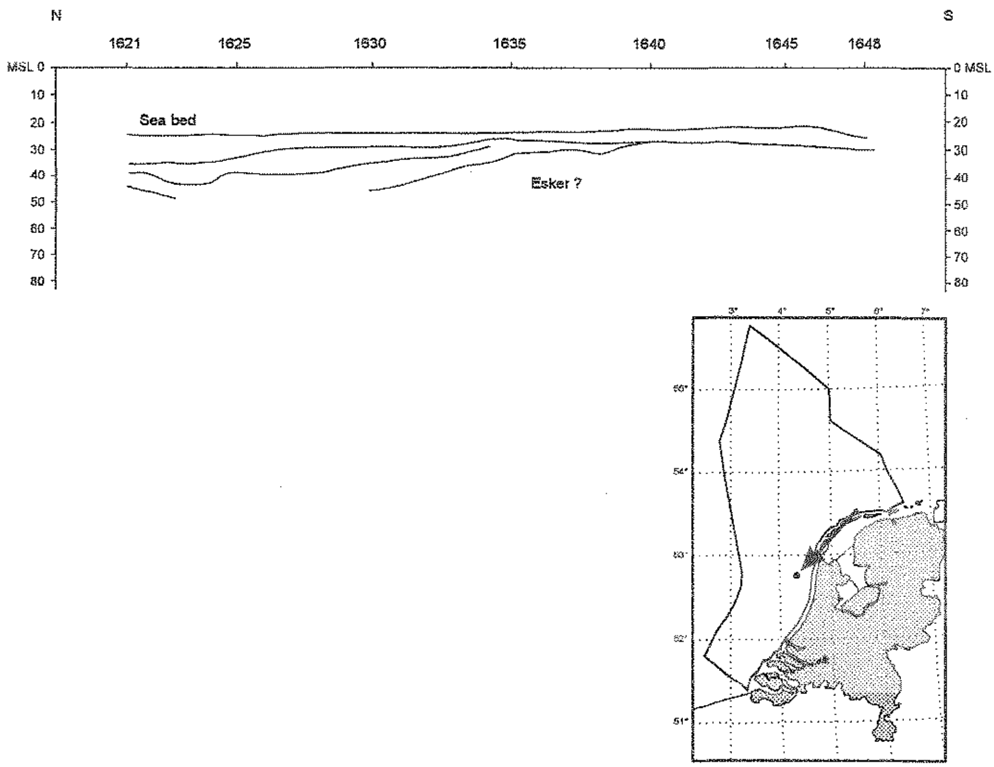


Fig. 57. Interpretation of a high resolution seismic profile over the Saalian esker-like feature recorded in block Q4.

nected the maximum extent of the continental ice sheet with that of eastern England in the region of Welton le Wold in Lincolnshire. Bowen et al. (1986) used the same extension as drawn by Oele & Schüttenhelm (1979) but named it the southern limit of Welton/Paviland/Saale Glaciation. Rappol et al. (1989) used a similar line to explain the north-south movement of the ice in the North Sea, although without any offshore evidence. A number of other authors, mainly from The Netherlands (Rappol et al., 1989), still assume that British Saalian ice entered the North Sea and extended east into the Dutch sector. Table 7 shows the correlation between the British and Netherlands Middle and Late Pleistocene Stages.

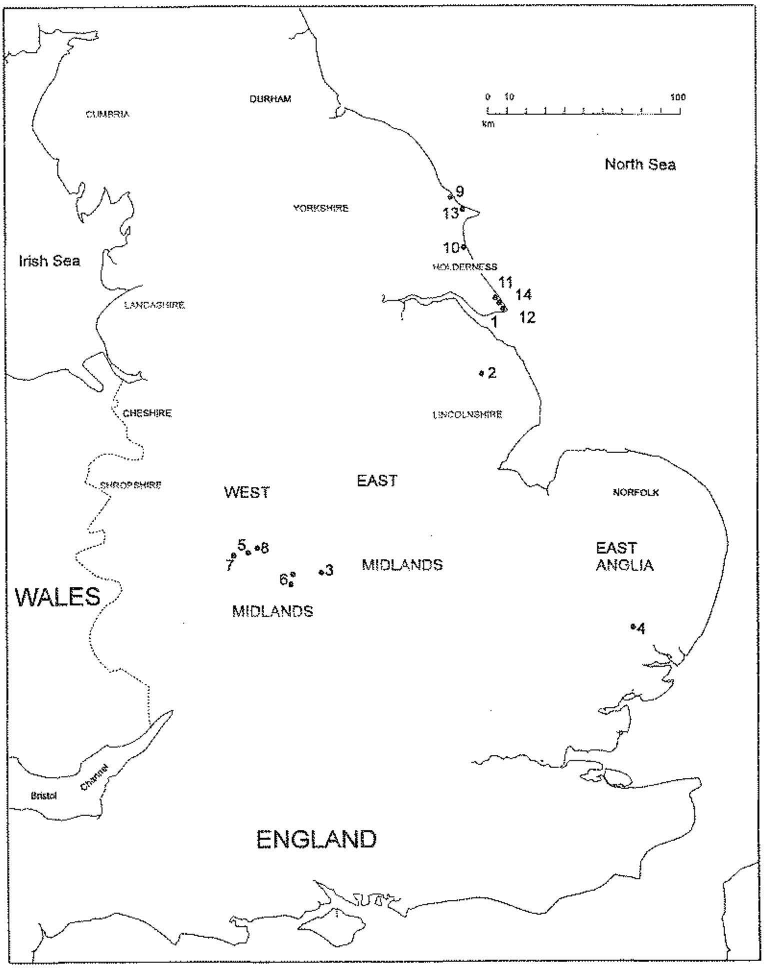
The main problem for age determination of the distinctive glacial deposits in England is that stratigraphic sequences are rare and workers have tended to develop interpretations based on assumptions rather than on firm evidences (Shotton, 1983a, Straw, 1983). Fig. 58 shows the locations mentioned in the text.

5.14.1 British ice sheet onshore in England

The evidence for a Saalian ice sheet onshore in England has been the subject of discussion for many years (Shotton, 1953, 1968, 1976, 1983a, b, 1986; Bishop, 1958; Rice, 1968, 1981; Mitchell et al., 1973; Bristow & Cox, 1973; Madgett & Catt, 1978; Perrin et al., 1979;

Fig. 58.
Locations in England mentioned in sections 5.13 and 5.14.

1 = River Humber
2 = Welton le Wold
3 = Wolston
4 = Gipping Valley
5 = Birmingham
6 = Baginton/ Lillington
7 = Quinton
8 = Nechels
9 = Filey
10 = Skipsea
11 = Withernsea
12 = Easington
13 = Speeton
14 = Dimlington



Straw, 1979; Douglas, 1980; Straw, 1983; Sumbler, 1983a and 1983b; Bowen et al., 1986; Rose, 1987, 1989; Gibbard & Turner, 1988, 1990; Gibbard et al., 1992; Lewis, 1994, and many others).

5.14.2 'Wolstonian' sites

Traditionally the Saalian has been correlated with the 'Wolstonian' in England (Shotton, 1968).

Shotton (1953) was the first to describe the stratotype which includes a succession of glacial, fluvioglacial and glaciolacustrine sediments near the village of Wolston on the river Avon in north Warwickshire and dated as 'deposited during the Penultimate major glaciation of the British Isles'. This succession was later designated as the Wolston stratotype (Mitchell et al., 1973) to replace an earlier informal term Gippingian (West & Donner, 1956). At two other locations near Birmingham, Shotton (1983b) has claimed that the Hoxnian (equivalent to the Holsteinian, see Table 7) Interglacial sediments separate two

glacigenic series, and referred the glacigenic deposits to the Wolstonian and Anglian stages respectively. Bowen et al. (1986) have suggested that the evidence for glaciation between the Hoxnian and Ipswichian (Eemian) Interglacials is far from clear, due to the fact that this glaciation was generally less extensive than the succeeding Late Devensian glaciation. As a result the glacial sediments of this earlier glaciation have been destroyed or obscured by the Late Devensian ice sheet. Bowen et al. (1986) describe tills in several areas which may have been deposited during a cold stage between the Hoxnian and Ipswichian Interglacials. They conclude 'that the only satisfactory evidence for glaciation in the interval between the Hoxnian and Ipswichian Interglacial Stages is the Welton/Basement/Warren House Tills of northeastern England'. In an attempt to give some indication of the Saalian ice limit in Britain they have produced a map of England and The Netherlands in which they showed the ice limit of the Welton/Paviland/Saale Glaciation from Welton le Wold in Lincolnshire extending in an east-south-east direction into the North Sea and then connect this with the Saalian limit at about 53° 30'N/4°E as tentatively drawn by Oele & Schüttenhelm (1979).

5.14.3 Baginton/Lillington Gravels

Rose (1987, 1989) demonstrated that the Baginton/Lillington Gravels, which according to Shotton (1953, 1976, 1983a and b) form the lower part of the Wolstonian at its type site, could be traced into East Anglia where they underlie glacial deposits of the Anglian Stage. Rose has proposed abandoning the term 'Wolstonian' for the Stage between the Hoxnian and Ipswichian stages until further evidence is available for glacial episodes during this interval. Rice & Douglas (1991) supported this interpretation and concluded that the fluvial Baginton/Lillington Gravels and the Baginton Sand which precede the 'Wolstonian' glacigenic deposits in the Midlands can be traced into East Anglia where they underlie deposits of Anglian age. Rice & Douglas argued that the term Wolstonian can be used as the local lithostratigraphic term for the glacial beds, and further emphasized the variable provenance of the tills thus highlighting the difficulties in assigning ages to glacigenic sediments.

Recent investigations at the Wolston Gravel Pit by Glasser & Lewis (1994) provide additional information about the relationship between the Wolston Clay and the Thrussington Till. The investigations clearly showed that the formation of the lake in which the Wolston Clay was deposited occurred after ice had passed over the site which deposited the Trussington Till. This confirms the earlier view of Perrin et al, (1979) that all pre-Devensian tills in Britain are most likely Anglian.

Straw (1991) stated that on the basis of the occurrences of tills and associated deposits that Lincolnshire and north-west Norfolk have been glaciated on probably four occasions:
1. Within the Anglian Stage, although most deposits have been reworked except in Norfolk
2. During the Wolstonian Stage Lincolnshire was glaciated, but the ice limit in Norfolk is still undetermined, and 3 and 4. An Early or Late Devensian glaciation in East Lincolnshire which reached Norfolk during the maximum, followed by deglaciation and a renewed advance.

Gibbard et al. (1992) described delta-like sediments formed by glacial meltwater at Tottenhill, Norfolk and suggested that an ice sheet entered the area from the north-west during a post-Anglian pre-Devensian glacial episode. According to pollen assemblages in underlying organic deposits the glacial deposits overlie Hoxnian sediments.

5.14.4 East Yorkshire tills

Another important till sequence is present along the rapidly eroding coast of East Yorkshire between Filey and Holderness. Here three tills are present, notably in upward sequence the Basement Till, the Skipsea Till and the Withernsea Till. They are locally separated by the laminated, freshwater Dimlington Silts (Catt & Penny, 1966; Penny et al., 1969). This sequence has been known and described since the last century (Phillips, 1829; Simpson, 1859; Lamplugh, 1879; Catt & Penny, 1966; Madgett & Catt, 1978; Edwards, 1981, 1982; Catt, 1987; Catt & Digby, 1988; Catt, 1991, and many others).
Straw (1983) described the Basement Till in east Yorkshire which is believed to be of 'Wolstonian' age and is overlain by Ipswichian beach sediments. The till overlies the Speeton Shell Bed which is regarded as Hoxnian in age (Melmore, 1935, Catt & Penny, 1966) (see Chapter 5.15.5).

The Basement Till at Dimlington is overlain by the Dimlington Silts which include mosses ^{14}C dated at 18,500 ± 400 BP (I-3372) and 18,240 ± 250 BP (Birm-108) (Catt & Penny, 1966; Rose, 1985). This indicates that the Basement Till was deposited before c. 18,000 BP and that the Skipsea and Withernsea tills postdate c. 18,000 BP.

Catt & Digby (1988) described 10 boreholes drilled in 1985 on the foreshore north of Easington (Holderness). Mineralogical analyses showed that the tills resemble the 'Wolstonian' Basement Till sampled on the beach and form the oldest till above the Chalk. They suggest that older glacial deposits (Anglian) were removed by Early Wolstonian marine erosion because of the high level of the Chalk compared with the much deeper level of the Chalk in Humberside and Lincolnshire. On Humberside and in Lincolnshire where chalk levels are much deeper, remnants of pre-Wolstonian tills are present according to Stather (1905) and Watts, (1959). Catt (1991) speculated that the "Older Drift" of the Vale of York is 'Wolstonian' in age. He also suggests that the erratics and heavy minerals in the deposits high on the Yorkshire Wolds do not correlate with any of the tills or glacial gravels of Devensian or 'Wolstonian' age but are more likely to be Baventian.

5.14.5 The Speeton Shell Bed

The Speeton Shell Bed is exposed in the cliffs of Filey Bay between beach level and 32 m above O.D and reaches a maximum thickness of 3 m. Edwards (1982) has given a detailed description of this sequence of sandy estuarine deposits containing a cool to temperate macrofauna and a cold, subarctic microfauna. He concludes that the sediments are pre-Ipswichian in age because of the cover of Early Devensian soliflucted chalk gravel, Devensian glacial deposits and also the tectonic disturbance of the deposits by ice. The soliflucted chalk gravel overlies the Speeton Shell Bed and pre-dates the Devensian ice advance. The bed is therefore considered to be of Early Devensian age. The orientation of the fold structures according to Edwards (1982) indicate a southerly flow of ice and a later overriding by the Devensian ice sheet. Based on pollen analysis West (1969) considered the bed to be Ipswichian zone II (f). Edwards (1982) however suggested that the bed was glaciotectonically deformed by two glaciations and is therefore Hoxnian in age. If Edwards' suggestion has any substance then the ice-pushing took place during the 'Wolstonian' or during an earlier Devensian glaciation and that furthermore the ice came from the North Sea and pushed the bed to its present elevated position. Gaunt et al. (1974) compared the low level shell bed of Speeton with the high level shell bed of Speeton and the Kirmington tidal de-

posits. The authors concluded that although the low-level bed is compatible with Ipswichian levels at Sewerby and elswhere, it becomes difficult to fit the Kirmington tidal deposits and the high-level shell bed of Speeton into an Ipswichian scheme, even allowing for a degree of isostatic or tectonic movement.

Knudsen & Sejrup (1988) concluded an Ipswichian age for the Speeton Shell Bed based on amino acid ratios of the foraminifera species *Elphidium excavatum*.
Wilson (1991) suggested however, that based on amino acid ratios of the mollusc *Macoma balthica* the Speeton Shell Bed was deposited during Oxygen Isotope Stage 7 and that the Basement Till was probably deposited during Stage 6. The Basement Till is regarded by Wilson as the most likely remaining representative of the Wolstonian Stage glaciation in Britain. According to Wilson the Speeton Shell Bed was deformed by 'Wolstonian' ice.
Bowen & Sykes (1991) argued that because of the mixed population which, in addition to *Macoma balthica*, also included *Arctica islandica* and *Macoma calcarea* it was not possible to reach a definite conclusion about the age of the Speeton Shell Bed.

Recent work on the Speeton Shell Bed was carried out by Thristlewood & White (1993) who studied the paleomagnetic and mineral magnetic properties. The mineral magnetic determinations supported the view of Edwards (1982) that the bed was not 'in situ' and was effected by weathering. The dips of mean magnetic foliation planes in the upper unit of the bed are, according to the authors, unlikely to be purely depositional in origin and they suggest a bodily rotation of the bed, and one that is consistent with ice-push.

5.14.6 The date of the Basement Till

Recent amino acid ratios dating of shell fragments collected from the Basement Till by Eyles et al. (1994) have shown that some of the molluscs have an amino-acid epimerisation ratio c. 20,000 BP. The authors therefore suggest that the Devensian glacial maximum in eastern England occurred earlier than has hitherto been suggested. The authors used three mollusc species in their study: *Arctica islandica*, *Mya truncata* and *Macoma balthica*. The first two appeared to pre-date the Devensian, but *Macoma balthica* revealed a cluster of 0.057 ± 0.011 D-alle/L-Ile and indicate a Late Devensian age. The authors suggest that the till was deposited by a glacier surging along the Yorkshire coast.

According to British Geological Survey geologists Tappin (pers. comm.) and Jeffery (pers. comm.) who have mapped areas offshore from East Yorkshire there is no evidence for Weichselian marine deposits in the area. East of the coast of Holderness the Devensian Bolders Bank Formation overlies pre-Quaternary, and Early and Middle Pleistocene formations. The marine Holsteinian Egmond Ground Formation is present in depressions in the area (Lott, 1986; Tappin, 1991; Cameron et al., 1992). However Eyles et al. (1994) found molluscs with D-alle/L-Ile ratio of 0.095 ± 0.014 indicating a Middle Devensian age and suggesting that derived molluscs do exist in this area.

5.14.7 Other offshore evidence for Saalian ice in the British sector of the North Sea

Oele & Schüttenhelm (1979) suggested that RGD borehole J14-1, located in the British sector, was drilled in a glacial basin of Saalian age. This borehole between 84 m and 66 m below MSL proved a laminated clay passing up into sandy clay, and containing a mixed British/Scandinavian pollen association of Tertiary, Mesozoic and Carboniferous age (Zag-

wijn, 1977). Foraminiferal analysis of samples between 80.19 m and 73.04 m below MSL recorded an association which indicated a cold environment with species such as *Elphidium excavatum f. clavata, Cassidulina reniforme, Nonion orbiculare, Buccella frigida* and *Elphidium asklundi* (Doppert, 1975).
This borehole, however, was drilled on the margin of an Elsterian valley (Cameron et al., 1986) and Lower Pleistocene (Waalian) deposits were reached (Zagwijn, 1977). According to Cameron et al. (1992) the overlying marine sediments are Holsteinian in age rather than Eemian (Cameron et al., 1986). This view supports the reinterpretation of the stratigraphy of this borehole, but tends to emphasize problems sometimes encountered with biostratigraphic correlations. North-west of borehole J14-1, BGS borehole 79/8 was drilled in which a glaciolacustrine clay was sampled between 78.50 m and 43.50 m below MSL. This clay may be the equivalent of the "Saalian" clay in borehole J14-1. The clay overlies Lower Pleistocene sediments which on the basis of pollen content, are regarded as Menapian in age (De Jong, 1981a). Borehole 79/8, like J141, was also drilled on the margin of a shallow (<100 m) "Elsterian" subglacial valley. The glaciolacustrine\marine clay deposits of both boreholes J14-1 and 78/08 most probably belong to the Elsterian infill of the valley, the Swarte Bank Formation (Balson & Jeffery, 1991).

In the Central North Sea several authors have described incised Late Saalian valleys more than 100 m below sea bed and indicating the presence of an ice sheet (see 5.12). According to Wingfield (1989) the discharge directions were respectively east, north-east and south-east.

5.15 Reconstruction of the maximum extent of the Saalian ice sheet in the Dutch sector of the North Sea

Based on previous work in the North Sea Overweel (1977) in his thesis reconstructed the maximum Saalian ice limit in the North Sea. The limit is connected to the maximum extent of Saalian ice in The Netherlands as shown by Maarleveld, (1953) and Ter Wee, (1962) and associated with glacigenic sediments and features discussed by Oele (1969, 1971) in the Dutch sector. In the British sector the ice limit is continuous with a belt of deeps (Flinn, 1967) and Scandinavian gravel deposits (Veenstra, 1971). The ice is thought to have extended as far as the Yorkshire coast and, farther north, to have crossed the British coastline near Aberdeen. Oele & Schüttenhelm (1979) also connected the Scandinavian ice sheet with a British ice sheet in the North Sea.

The reconstruction of the maximum extent of the ice sheet by the present author (Fig. 59) is based on study of the legacy left by glacial sediments and of landforms glaciated by the ice sheet. Within the maximum extent of the Saalian ice in the Dutch sector of the North Sea till plateaux and tongue-shaped basins were formed together with deformation structures along their margins. In addition subglacial channels, esker-like features, and ice-contact gravels were also formed. In the area west and north of the reconstructed ice margin none of the above features have been recorded in boreholes or are evident from seismics. Glaciolacustrine and fluvioglacial deposits overlying Saalian periglacial sediments dominate the area west and north of the ice margin. The ice margin in the North Sea forms a continuation of the north-west/south-east trending margin on land. Only in block P15 has the ice moved further south. During advance of the ice from the north-east, and in the north-eastern and western parts of the Dutch sector, tongue-shaped basins were formed pointing to the formation of a lobate ice margin. The subglacial valleys which are present between

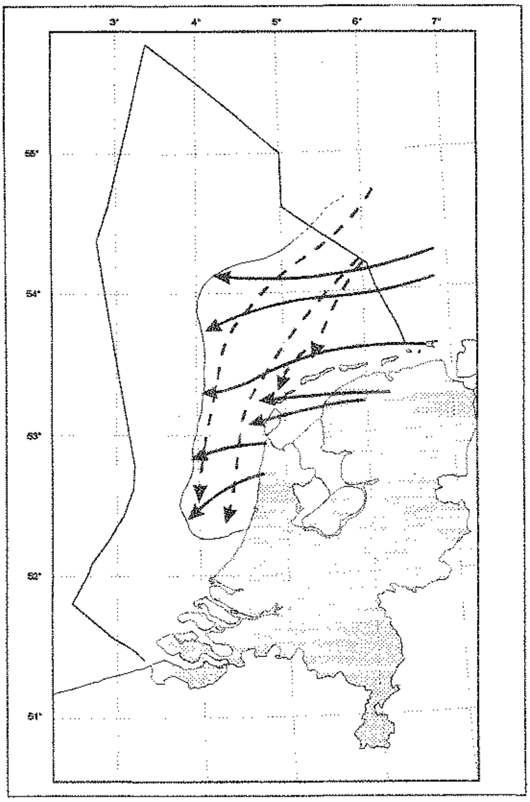


Fig. 59. The maximum extent of the Saalian ice sheet in the southern North Sea showing suggested flow directions of ice during the south-easterly and north-easterly flow.

53°N and 54°N latitude indicate a closed ice-front in that area while south of the 53°N a lobate margin again appears to be developed as was present in the eastern part of The Netherlands. In this area no tills have been found so far. The maximum extent of the ice limit is in this area based on the presence of the tongue-shape basin and ice-push structures.

The glacio-isostatic compensation movement resulting from the presence of an ice load in the eastern part of the southern North Sea finds expression in the thickness of Eemian marine sediments in the coastal area of The Netherlands and their progressive thinning in westerly and north-westerly directions outside the Saalian ice limit. At about 3°E, Eemian marine sediments are absent or only very thin as can be seen from the 1:250,000 Quaternary map Flemish Bight (Cameron et al., 1984b). This is probably due to the rapid amelioration of the climate at the end of the glaciation and the subsequent rise of sea-level which was much quicker than the glacial rebound after the crustal subsidence caused by ice loading. The 'earth's' response on the unloading after deglaciation is delayed (Lambeck, 1990).

According to Rappol (pers. comm.) the line of the maximum extent of the ice sheet in the Dutch sector of the North Sea is too close to the coast of the northern Netherlands to allow the ice to change direction from a north-east/south-west to that of a north/south or north-west/south-east direction. Rappol (1987) and Van den Berg et al. (1987) assumed that the ice sheet extended much further north in the North Sea area in order to explain the origin of the north-east/south-west trending Hondsrug in the eastern Netherlands. According to them the ridge could have been formed only by ice entering the present land area from the north-west.

Based on data collected by RGD, the extent of the Saalian ice sheet in the North Sea is far enough to the west to allow ice to enter the northern Netherlands from a north-easterly direction. There is a possibility however that at the end of the glaciation and due to a rapid sea-level rise sea water entered the Norwegian Trench and the Elbe valley in the German Bight effectively cutting off the ice stream towards the south-west from its source. The effect of cutting off the ice source in the North Sea and the northern Netherlands resulted in

the ice flow changing to a different direction e.g. to the south (Rappol et al., 1989; Van der Wateren, pers. comm. 1994).
The continuation of the Saalian ice limit in the German sector is uncertain and mainly based on older studies (Pratje, 1951; Sindowski, 1970; Figge, 1983; Cameron et al., 1993). The ice limit in the Danish sector has been established locally by Foged (1987) who found outcrops of Saalian moraines at approximately 45 km and 61 km from the Danish North Sea coast and at a depth of between 25 m and 30 m below MSL. He suggested a connection between these moraines and the Horns Rev end moraines in the North Sea west of the Danish town of Blåvands Huk (Krog, 1979). On seismic profiles the reflector at the top of the Saalian sediments can be traced over a distance of about 104 km from the coast out to sea where it disappears at a depth of 65 m below MSL. According to Foged (1987) there are no indications of the presence of till west of this area. Salomonson & Jensen, (1994) observed Saalian glacial channels in the Danish sector of the North Sea, although they were not mapped. Based on the available data a preliminary Saalian ice limit through the Dutch, German and Danish sectors was drawn by Cameron et al. (1993).
Unfortunately, the governments of both Germany and Denmark are not currently carrying out a reconnaissance survey programme in the North Sea.

Two main flow directions of the Saalian ice can probably be distinguished in the Dutch sector: the first, as also observed on land, has a south-westerly direction, the second from a north-easterly direction (Fig. 59). When the ice flowed south-west ice marginal valleys were formed along the line of the maximum extent of the ice sheet. During the north-eastern flow these valleys were filled with ice and became used as basins.

5.16 Drainage during the Saalian glaciation

During the Saalian glaciation the rivers drained through the Strait of Dover which became open during this period. The ice barrier in the northern and central Netherlands forced the rivers into a southerly direction. Sea-level was lowered to about 130 m ± 10 m below present level (Chappell & Shackelton, 1986; Lambeck, pers. comm.). During the subsequent Eemian Interglacial, molluscs from the Lusitanian zone could enter the southern North Sea through the Strait of Dover (Spaink, 1958). The glacial drainage flowed in both northerly and westerly direction as concluded from the distribution of the meltwater deposits. The locations of boreholes mentioned in Chapter 5 are shown in Table 4.

5.17 Conclusions

The Tea Kettle Hole Formation is mainly present in an area within and around the maximum extent of the Saalian ice sheet. Because of the depth to the top of this formation the sediments have been mainly sampled in deeper boreholes. The number of such boreholes in the southern K and L-blocks is greater than in the remaining blocks and this fact reflects the more widespread apparent occurrence of the formation.

The sediments of the formation are of periglacial origin, deposition taking place during cold phases preceding the glaciation.
The sediments are mainly fluvio-periglacial, but local aeolian deposition also took place. The great difference in thickness of the formation points to the infill of open channels at the end of the Holsteinian Interglacial.

In none of the boreholes do Saalian periglacial deposits cover Saalian glacigenic sediments. This is probably due to the fact that after the retreat of the ice on the onset of the Eemian Interglacial, a rapid increase of temperature and consequently of precipitation, took place. The deposition of wind-blown sands came to a standstill almost immediately and a vegetation cover became established over the landscape. During the Eemian transgression the Saalian surface was drowned rapidly.

The age of the Tea Kettle Hole Formation in the North Sea is Early to Late Saalian.

The glaciolacustrine deposits of the Cleaver Bank Formation are mainly present in a very large area north and north-west of the line of the maximum extent of the Saalian ice sheet. Within the area which was covered by ice, and also in a narrow zone around it, the Cleaver Bank Formation is only locally present in what are most likely subglacial channels. This is probably caused by a rapid advancing of the ice sheet under cold climatic conditions when only small amounts of meltwater became available. Another possibility is that the sediments were deposited in the glaciated area during the advance stage of the ice, but were subsequently eroded when they became covered by the ice and have been preserved only in the depressions.
The wide occurrence as well as thickness of the formation indicate that during its maximum extent the ice was stagnant probably for a long period or that high amounts of meltwater were produced.
The surface of the formation dips slightly towards the north-west from between 30 m and 40 m below MSL in the present coastal area to 72 m below MSL in the central F, central and northern E blocks and in block A18. West of the line of the maximum extent of the ice sheet in the K blocks the formation is found only locally in boreholes probably indicating greater discharge of meltwater in a north-north-west direction.

In the seismic profiles of the K blocks there are only indications of the local presence of the Cleaver Bank Formation. In the P-blocks the Cleaver Bank Formation has been sampled in only one borehole, and this was drilled in a glacial basin.

The thickness of the formation varies generally between 4 m and 6 m. In the northern part of the Dutch sector however thicknesses of up to 29 m are locally found (block B13). Probably the formation once had a much greater thickness over its entire area of distribution, but it has been affected and subsequently eroded by the marine transgression during the Eemian Stage. This theory is supported by the fact that in none of the boreholes penetrating the base of the Eemian, marine low energy sediments are found. The layer at the base of the Eem Formation is always formed by a transgressive sand body which probably consists of reworked Saalian fluvioglacial sediments.
The thickness of over 20 m in the northern part of the Dutch sector is probably due to sediments derived from an ice sheet located south of the Norwegian Trench. This view is in accordance with the extension of the glaciolacustrine sediments in the British sector north of 54°N where the deposits extend as far west as 1°E (Cameron et al., 1992).

In only one borehole in the northern part of the Dutch sector does the formation appears to contain pollen reflecting the existence of an open landscape with a vegetation consisting mainly of herbs and present during the deposition of the glaciolacustrine clay. All other analyses show only spectra with reworked Tertiary pollen. In this northern area the deposits are present at relatively shallow depths i.e. at less than 50 m below MSL and their

thickness is much greater than in the area south of 55°N. Presumably deposition took place during a phase of deglaciation and at which time the delta became subaerial. In the area south of 55°N the deposits are present at greater depth as described above and contain only Tertiary pollen. The absence of younger pollen was probably due to cold conditions with a cover of ice even during the summer. Another possibility is that the vegetation was sparse and the abundance of fossil pollen much greater than the production of autochthonous pollen (Zagwijn, pers. comm.).

Only locally e.g. boreholes E1-10, E8-4, F3-5, and L11-71 is sparse ice-rafted debris (dropstones) found. It is not clear if this debris can be related to grounded icebergs.

The Cleaver Bank Formation has the same genesis as most of the glaciolacustrine deposits of the Elsterian Swarte Bank Formation and the Weichselian Dogger Bank Formation. The lithology also resembles both those formations. As discussed above however, the Cleaver Bank Formation can readily be distinguished from these other formations on high resolution seismic profiles.

From the position of the formation between Holsteinian marine and Eemian marine depos its or the Weichselian Dogger Bank Formation, it is concluded that the age of the formation is Saalian.

The Saalian till of the North Sea occurs in two separate areas: I in the Ems estuary between the Dutch coast and the German island of Borkum and II between 4° E and 5° 20' E and 55° 03'N and 53° N. In between these two areas no till has been located. The absence can possibly be explained by nondeposition or by erosional processes during the marine Eemian and/or Holocene transgressions.

The depth to the top of the till varies in area I from >12 to 16.1 m below MSL with a thickness ranging from 1 m to 3.50 m. In area II the depth of the till ranges from about 18 m in the shallow coastal zone to 51.10 m in the west and 46.50 m in the north of its area of occurrence. Locally in valleys the top of the till lies at greater depth as for example on the east coast of the island of Texel where the top lies at 35.30 m below MSL. Another example is found in the north, in borehole G16-22 where the top of the till occurs in a small tongue-shaped basin and was sampled at 67.05 m below MSL.

In both areas the till mainly consists of greenish-grey to brown-greenish-grey, firm to very firm, very sandy to sandy silt with fine to very coarse gravel (2 mm to 30 mm) composed of crystalline cobbles, flint, quartz and chalk pebbles. Locally a sand layer is intercalated, but apart from that, the sequence is interpreted as one single till layer.

The tills in the North Sea are not decalcified like most of the onshore tills because they are covered by marine Eemian sediments and during the Weichselian no decalcification took place at depth.

The Borkumriff Formation has the same lithology as the till of the Drente Formation in the Netherlands.

The age of the Borkumriff Formation is Late Saalian.

Most of the Saalian gravels have been reworked during succeeding marine transgressions and by sea bed trawling. The only occurrence of probable non-reworked deposits lies north-west of Texel.
Due to lack of samples it has not been possible to distinguish between the Baltic and Swedish tills as has been possible on The Netherlands land area.

Fluvioglacial deposits of the Molengat Formation are only occasionally found in the Dutch sector of the North Sea. Probably the deposits were originally distributed more extensively, but subsequently have been largely reworked and transported during the Eemian transgression.

The age of the Molengat Formation is Late Saalian.

The Eem Formation overlies almost the whole area which was glaciated during the Saalian glaciation. The marine sediments often contain some gravel of Scandinavian origin. The Eemian transgressive sea probably reworked Saalian fluvioglacial sandy deposits.

The small, shallow glacial basin in the southern G and F blocks is the northernmost one observed. The basin is evidence that the ice sheet must have had a more northern extent in the Dutch sector than several authors have previously described (Cameron et al., 1993).
A glacial basin, west of the Dutch coast and within the area of the maximum extent of the Saalian ice sheet, is thought to form a continuation of a series of basins which are known from the land area of the Netherlands. The basin is less deep than those on land, and this is in agreement with a decrease of the depth of the basins from east to west as proposed by De Gans (1991).
The infill, as interpreted from numerous high resolution seismic profiles differs from the infill as observed in the older, subglacial Elsterian valleys. The thick infill of Eemian marine sediments points to the fact that the valley was partly open at the end of Saalian glaciation a similar situation being present in the basins of the western Netherlands.
Deformation structures in the subsurface between the Dutch coast and 4°E (see below) are indications of the presence of a glacier in this area and consequently for the probable presence of more basins; additional seismic surveys may well reveal such basins. The way in which the onshore and offshore valleys may be connected has yet to be investigated in detail.

Deformation structures resulting from ice-pushing are observed on high resolution seismic profiles at a great number of locations between the island of Texel and the limit of the southern extent of the ice sheet. Lower Pleistocene formations were sampled in boreholes at an extremely high level below the sea bed. The area with deformation structures offshore forms a continuation of that observed onshore along the glacial basins in the western Netherlands.

The occurrence, shape and axial profile of the valleys within the area of maximum extent of the Saalian ice sheet makes genesis by meltwater under high pressure the most likely mode of formation.

The thin layer of glacial sediments at the base of the valleys together with the main infill of Eemian marine sediments is evidence that the valleys were probably filled with ice until the end of the glaciation.

Subglacial valleys are probably much more abundant in the L and M blocks, and have to be mapped by means of a sparker as source. The north-south trending valleys in the F and G blocks most likely belong to a later phase of the glaciation and were formed as a result of the retreat of the ice sheet from north to south. Another possible way of formation was that, in complete contrast, the ice came from the north. Since no evidence has been found for such a western extension in the area north of the ice-limit as drawn in Fig. 59 the first possibility is regarded as most likely.

The north-west/south-east trending valleys in the L-blocks were probably formed during an earlier advance when the ice came from the east-north-east. The genesis of the valleys differs from that of the valleys during the Elsterian glaciation in that the Saalian valleys are much shallower and narrower. The braiding pattern of the Elsterian valleys has not been established. At the base of the valleys a parallel seismic lamination is locally visible indicating an infill of fine sediments under low energy sedimentary conditions (borehole F17-5).

In one case, in block Q5 the presence of an esker-like feature is thought to have been established. More detailed seismic and sampling surveys over this location are required to map the geometry of these gravel bodies in order to confirm that these features are definitely eskers.

The publications reviewed indicate that there is no unequivocal evidence for the occurrence of a glacial event in the North Sea Basin between the Hoxnian and Ipswichian Interglacials. Such tentative evidence that does exist suggests that any glaciation during this interval was much less extensive than the Anglian and Devensian glaciations.

The interpretation of the amino acid racemization/epimerisation ratios shows that most of the dated species pre-date the Devensian. The findings of Eyles et al. (1994) confirm the view of Cameron et al. (1992) that there is no evidence so far for an ice sheet in the interval between the Hoxnian and Ipswichian. This creates a problem however as to establishing from which sediments the molluscs were derived. The older specimens were, according to Eyles et al. (1994), derived from older formations while *Macoma balthica* was apparently derived from Devensian marine deposits, which have yet to be found. In the Dutch sector no evidence is found for a Late Weichselian marine incursion.

According to Balson & Cameron (1985), Lott, (1986), Jeffery et al. (1989), Tappin (1991), Balson & Jeffery (1991) and Cameron et al. (1992) no glacigenic deposits or scaphiform valleys of Saalian age have been found in the British sector of the North Sea south of 55°N. This suggests that the area was never covered by a grounded ice sheet.

In the Dutch sector of the North Sea the limit of the Saalian ice sheet is now reasonably well established. In the British, and more especially in the German and Danish sectors, there is still considerable uncertainty and research is still required.

Chapter 6

The Weichselian glaciation in the North Sea

6.1 Introduction

Twice during the Weichselian glaciers extended over large areas of Great-Britain. The early glaciation probably took place during the Early Weichselian before 46,000 BP (Worsley, 1991). No evidence for an Early Weichselian glaciation has, however, been found so far in the southern North Sea (Balson & Jeffery, 1991; Cameron et al., 1992). Evidence for an Early Weichselian Scandinavian ice sheet in north-western Europe is still a subject of debate (Houmark-Nielsen, 1987). Recent investigations in the northern North Sea by Sejrup et al. (1994) indicate that the maximum Weichselian glaciation in the northern North Sea took place between 29,400 and c. 22,000 BP with a coalescing British and Scandinavian ice sheet. According to Sejrup et al. (1994) during the second advance of the Weichselian ice sheet between 18,500 and 15,100 BP the British and Scandinavian sheets did not coalesce.
The earliest publication regarding a Weichselian ice sheet in the North Sea was by Valentin (1955) who made a detailed reconstruction of the maximum extent of the British and Scandinavian ice sheets of the last glaciation. The interpretation was based on the occurrence of deep open valleys like the Well Hole (84 m below sea bed), Markhams Hole (82 m below sea bed) and the Botney Cut (66 m below sea bed) which he regarded as late glacial subglacial channels. Furthermore Valentin to support this theory made use of other morphological features and the occurrence of superficial sediments as shown on hydrographic and fishery charts. In his reconstruction the southern limit of the ice sheet extended as far east as the Cleaver Bank south-west of the Dogger Bank. North-west of the Dogger Bank the Scandinavian and British ice sheets became connected. He further suggested that the deep valleys north of the Dogger Bank, such as the Devils Hole (243 m below sea bed), Swallow Hole (159 m below sea bed) and Fladen Ground valley (295 m below sea bed), had also been formed subglacially. The limit of the British ice was drawn east of these deep depressions. The southern limit of the Scandinavian ice sheet was thought to extend from northern Germany through Jutland thence towards the west to the northern margin of the Dogger Bank and the limit of the British ice sheet. Between the Dogger Bank and the German Bight he envisaged a proglacial lake in which the superficial sediments of the Oyster Grounds were deposited. The sediments had, according to mineralogical investigations by Baak (1936), a Scandinavian provenance. Recent studies in the Oyster Grounds area have indicated that the age of the superficial sediments is Late Holocene marine (Zuo et al., 1989; Laban et al., 1995b).

Valentin (1955) assumed that drainage took place through the Strait of Dover which was opened up during the Saalian glaciation although sea-level must have been about 100 m lower than at present.

As discussed below the interpretation by Valentin of the extent of the British ice and the genesis of the valleys is largely in accordance with most recent information and present day studies. For instance later authors have confirmed the British origin of the gravel in

the area of the Cleaver Bank (Veenstra, 1965; Zagwijn & Veenstra, 1966; Dijkmans, 1981) (see Chapter 6.5).
The Scandinavian ice sheet did not enter the German Bight (Behre et al., 1979) and extended only into the northern part of the Danish sector. In Schleswig-Holstein five advances of Weichselian ice sheets have been recognised based on the occurrence of two till complexes in the Baltic Sea cliffs. The lower complex corresponds to the first four advances (Stephan & Menke, 1977; Stephan, 1988) while the upper complex corresponds to till of the younger ice advance (Piotrowski, 1994b). In Central Denmark six Weichselian tills are recognised (Houmark-Nielsen, 1987).

Oele, (1969) was not certain whether the Weichselian ice sheet extended at this time into the Dutch sector. He equated Weichselian till occurrences found near the Cleaver Bank with Saalian tills sampled in the eastern part of the Dutch sector and in The Netherlands.

During the Weichselian glacial maximum and at approximately 18,000 BP the sea-level dropped substantially, probably by more than 130 m below present level. There are many different views on the relative position of sea-level during the Weichselian and opinions vary widely (Curray, 1965; Milliman & Emery, 1968; Jelgersma, 1961, 1979). Jardin (1979) suggested that the relative sea-level was between -60 m and -70 m Ordnance Datum during the glacial maximum.
Jansen et al. (1979b) calculated a lowest sea-level of about 110 m below present day level at about 15,000 B.P. and not at 18,000 B.P. as previously suggested. According to Jansen the difference was caused by regional isostatic movement. He drew a coastline at the transition between the Fladen Deposits as defined by Jansen and the overlying Witch Deposits. (the Fladen and Witch Deposits are both members of the Witch Ground Formation according to Stoker et al. (1985a, 1985b)). Streif (1990b) remarked that during the Weichselian Stage the sea-level in the southern North Sea has always been 35 m below present level. According to Oele & Schüttenhelm (1979) however the sea-level was more than 50 m below the present level during the Weichselian Stage.

Early Weichselian fresh water deposits in the southern part of the Dutch sector were sampled at depths up to 48 m below MSL indicating a sea-level fall of at least 50 m during that time. The fresh water deposits overlie open marine to brackish marine Eemian sediments (see Chapter 6.2).

The depth of boreholes and samples are given in metres below Mean Sea Level (MSL). The lower sample is quoted first and the upper sample second. For the location of boreholes, see Table 5.

6.2 Brackish marine to lacustrine deposits (Brown Bank Formation)

The oldest deposits which indicate the onset of the Weichselian Stage and reflecting a sea-level lowering, are marine to brackish/marine, brackish and lacustrine deposits in the central part of the southern North Sea. They are referred to the Brown Bank Formation. The sea-level at the time is thought to have dropped at least 48 m below present level.
The formation is named after the Brown Bank which lies between about 52° 20'N and 52° 45'N/ 3° 20'E (Cameron et al., 1984b).
The first sample (22b) of these deposits was recovered from the anchor of the Dutch navy Vessel H.M.S. Luymes (Van Eerde, 1963). Zagwijn (1963) concluded that, based on pollen

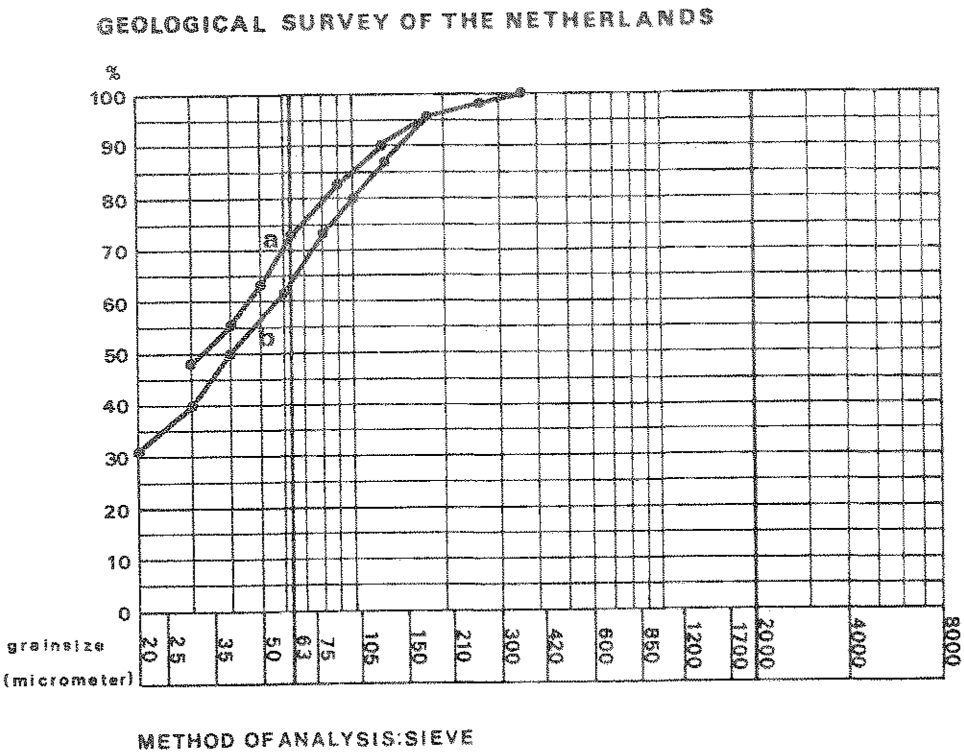


Fig. 60. Grain size analyses of the Brown Bank Formation in boreholes K18-16 (a) and K18-21 (b).

content, the deposits were Late Eemian (pollen zone 6b) to Early Weichselian (pollen zone EW Ia). The deposits were later described by Oele (1971) as the Brown Bank Bed.

In the Dutch sector the formation has been sampled in boreholes and cores at 97 locations. It consists predominantly of stiff, greyish-brown laminated clay (Fig. 60). The clay is locally bioturbated (Fig. 61) and contains cracks filled with Holocene shelly sand. The thickness varies between 2 m and 5 m.
On high resolution seismic profiles the formation has been traced over large areas, often showing a parallel seismic lamination (Fig. 7).

More recently pollen analyses has been carried out on samples from several cored boreholes. In borehole P5-4 the formation, sampled between 40 m and 36.80 m below MSL, consists of a grey, laminated sandy clay with fine shell fragments at the base. Towards the top of the sequence the lamination decreases, the clay becoming greyish-brown to brownish-grey, stiff to very stiff, and rich in calcium carbonate. The formation is overlain by a sequence of Early Holocene tidal flat and open marine deposits, and is underlain by marine Eemian and older sediments.
The clay in this borehole contained a pollen association which at the base included the *Pi-*

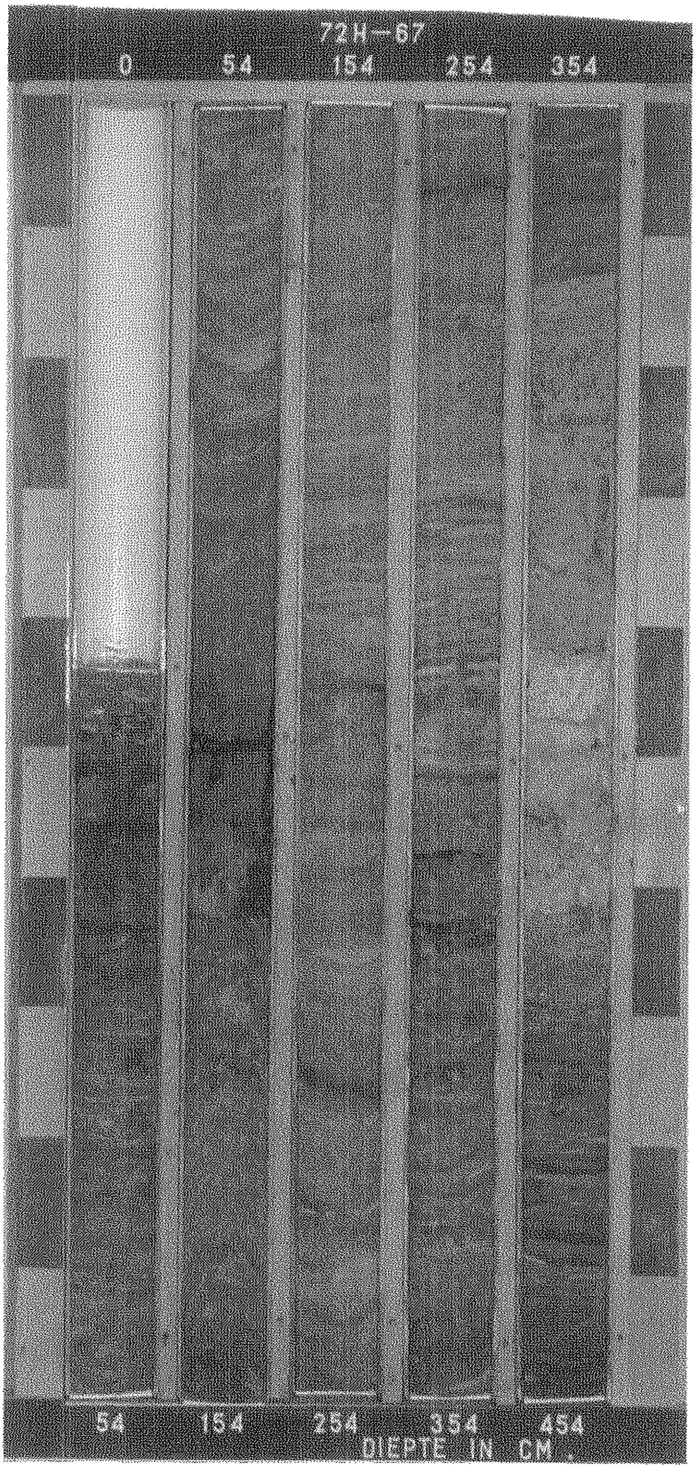


Fig. 61. Photograph of the Brown Bank Formation in core P7-8 (depth in cms). The upper c. 8 cm consists of Holocene sand. The 'bent' lamina are caused by disturbance during coring. Local bioturbation is visible at about 294 to 304 cms.

nus-Picea zone dated as Late Eemian (pollen zone E6). A pollen assemblage with a high percentage of herbs was obtained from the upper part of the clay and indicates a cold phase. Pollen of *Calluna*, for instance, reach percentages of >10%. The clay has been dated as Early Weichselian, pollen zone EWIa (Zagwijn, 1961; 1970c) (Fig. 62). Ostracod analyses on samples of pollen zone E6 indicated a marine environment of deposition while those of pollen zone EWIa indicate deposition in fresh water conditions (Du Saar, 1970b, c). These analyses broadly accord with age determinations by pollen analysis. By contrast, foraminiferal analysis revealed only 15 marine specimens of Eemian or Holocene age, and which are regarded by Toering (1970) as having been reworked. Core L16-1 consisted between 30.40 m and 31.60 m below MSL of sandy laminated clay with organic matter. The pollen assemblage shows a dominance of *Pinus*, *Betula*, *Alnus*, *Abies*, and *Picea* while thermophilous trees were present in low percentages indicating the youngest part of the Eemian Interglacial, pollen zone E6b (De Jong, 1970). The sediments were rich in diatoms with 54 to 60% of shallow marine and a low percentage of brackish and fresh water species. Indicators for an Eemian age are poorly represented with species like *Edictya oceanica*, *Rhabdonema adriaticum* while species pointing to deposition in an arctic environment include *Fragilariopsis cylindrus*, *Fragilariopsis oceanica* and *Porosira glacialis* (Du Saar, 1970a). The arctic species indicate the presence of floating ice (De Wolf, pers. comm.). The shallow water points to near coastal conditions probably due to the sea-level fall at the beginning of the Weichselian glaciation.

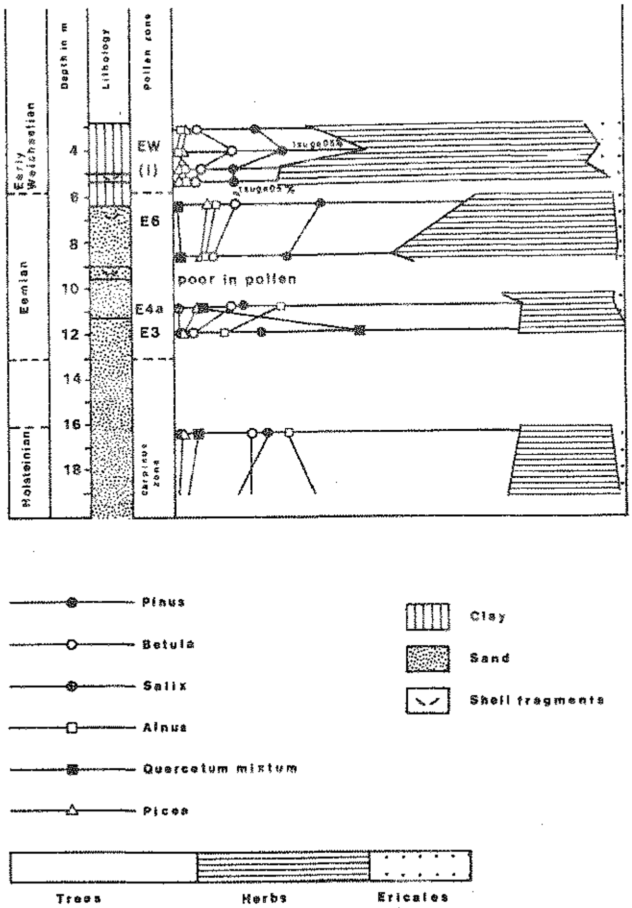


Fig. 62. Pollen diagram of the Brown Bank Formation in borehole P5-4 (Zagwijn, 1970c).

In the southern K-blocks outliers of the formation have been sampled in several boreholes (Cameron et al., 1986). In borehole K15-4 the formation, sampled between 37.15 m and 34.15 m below MSL, consisted of very fine clayey sand. The pollen content shows a high percentage of herbs and thermophilous trees. Based on the pollen content, Zagwijn (1977)

dated the deposit as Early Weichselian, but it was not possible to determine if sedimentation took place during stadial or interstadial conditions.

In borehole F14-13 a greyish-brown, non-calcareous clay with organic matter was sampled between 48.40 m and 46.79 m below MSL. Diatom analysis of the clay revealed a poor flora with sparse Eemian species. The clay was deposited in a fresh water environment with a chloride content of less than 50 mg/l (Du Saar, 1969). Pollen analysis of the clay indicated a Late Dryas Stadial (pollen zone LWIII) or older (Pleniglacial) age (see Table 8). The clay is overlain by an Early Holocene sequence 0.78 m thick, consisting of Preboreal peat (pollen zone H Ia) and Preboreal to Boreal clay with silty sand on top (pollen zone Ic to IIa). ^{14}C dating of the peat recorded an age of 9935 ±55 BP (GrN 5758) (De Jong, 1973a, b). The Late Weichselian fresh water clay is referred to the Brown Bank Formation as indicated by the similar lithology of the Early and Late Weichselian deposits (Laban et al., 1995a).

Table 9 shows schematically the relationships between the formations.

Further to the east and in two boreholes which were drilled in local depressions infills of clay were recorded. In borehole G18-25 between 45.40 m and 44.40 m below MSL, a brownish-grey clay is present with shell fragments and some gravel. In borehole G17-19 similar brownish-grey clay has been sampled between 44.60 m and 43.05 m below MSL. According to the pollen content (Veldkamp, 1994), the clay was deposited during the Late Eemian sea-level lowering (pollen zone E6). The clay also belongs to the Brown Bank Formation (Laban et al., 1995a).

Near the south-west coast of the province of Zuid-Holland and between Hoek van Holland and Voorne (south-western Netherlands) the sandy sediments of the fluviatile Kreftenheye Formation are overlain by fluviatile clay. The clay has been sampled in several boreholes in this area. Pollen analyses recorded a percentage of herbs and indicate a Late Weichselian age, pollen zone LWIII (Late Dryas Stadial), (Zagwijn, 1968).

The formation also extends to the west into the British sector (Cameron et. al., 1984b; 1989)

In areas where the Brown Bank Formation is exposed on the sea bed numerous mammal bones have been trawled by fisherman from the clay bed (Erdbrink et al., 1990; Van Bree & Post, 1994). The assemblage definitely belongs to a cold, Late Pleistocene fauna (Van Kolfschoten & Laban, 1995).

The environment of deposition was initially marine during the Late Eemian, changing to brackish marine by the growing influence of British rivers as well as those of the rivers Rhine and Meuse. Finally deposition was predominantly limnic.
The geometry of the formation is shown in Fig. 63.

6.3 Fluvioglacial deposits (Well Ground Formation)

Along the south-east margin of the maximum extent of the Weichselian glacial sediments, fans of fluvioglacial sands are locally present underlying Holocene sediments. The deposits have also been sampled below glacial sediments. Locally they overlie Weichselian till and

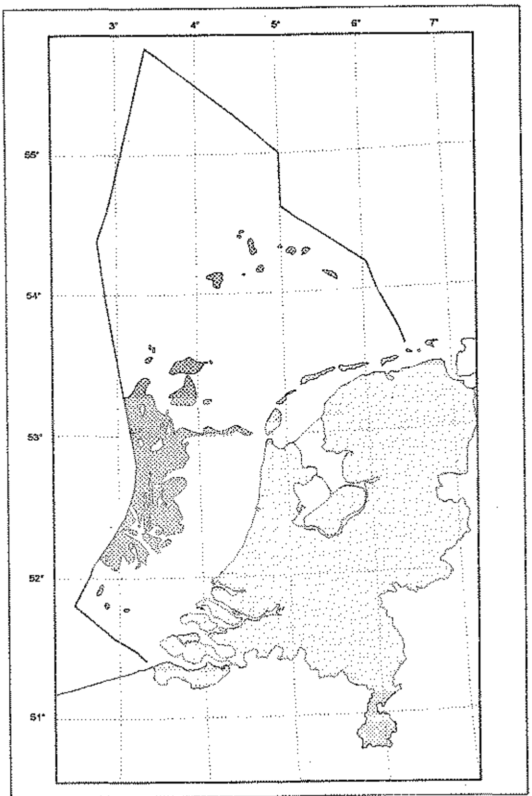


Fig. 63. Geometry of the Brown Bank Formation. The depth to the top varies between 40 m and 45 m below MSL in the area between 52°N and 54°N, and between 45 m and 50 m below MSL north of 54°N.

glaciolacustrine sediments. The deposits are named Well Ground Formation after the Well Ground in the British sector south of the Dogger Bank (Cameron et al., 1986).

In borehole K1-10 the formation, sampled between 47.85 m and 44.85 m below MSL, consists of very fine to fine silty sand with some fine gravel. The calcium carbonate content increases upwards. The sediments, poor in pollen (De Jong, 1981b), are underlain by Weichselian Pleniglacial deposits (De Jong, 1981b) of the Twente Formation and overlain by marine Holocene sediments.
In borehole E18-4 the formation, sampled between 50.40 m and 48.40 m below MSL, consists of olive-brown, very fine sand with sparse mica and, at the base, some fine gravel (flint and granite). The formation is overlain by diamicton of the Bolders Bank Formation and is underlain by marine sediments of the Eem Formation (see Table 11).

The formation has been sampled in 18 other boreholes in the Dutch sector. It consists mainly of well sorted, very fine- to medium-grained sand, locally slightly silty, with mica and sparse fine gravel (Fig. 64). The calcium carbonate content varies from non-calcareous to slightly calcareous. The thickness varies from 2 m to approximately 4 m.

Heavy mineral analyses were carried out by Dijkmans (1981) on samples from borehole E16-39 at depths of between 47 m and 46.50 m below MSL. Dijkmans analyzed the heavy mineral content of 10 mineral groups in six fractions ranging from 53 to 420 μm (Fig. 65). The assemblage consists of 30 to 50% garnet, and high percentages of amphibole (8 to 28%) and pyroxene (4 to 19%). Pyroxene percentages increase in the fractions >150 μm. Epidote decreases from 14% in the finest fractions to 4% in the coarser fractions, whereas alterite increases from 2% in the finer fractions to 15% in the coarser fractions. The same heavy mineral content was found by Dijkmans in samples from borehole K1-10 described above. The assemblage is also comparable with those found in the overlying till (see Chapter 6.7).

The formation was deposited during the advance and retreat of the ice in a proximal proglacial position and is overlain by glaciolacustrine clays and till or Holocene marine sedi-

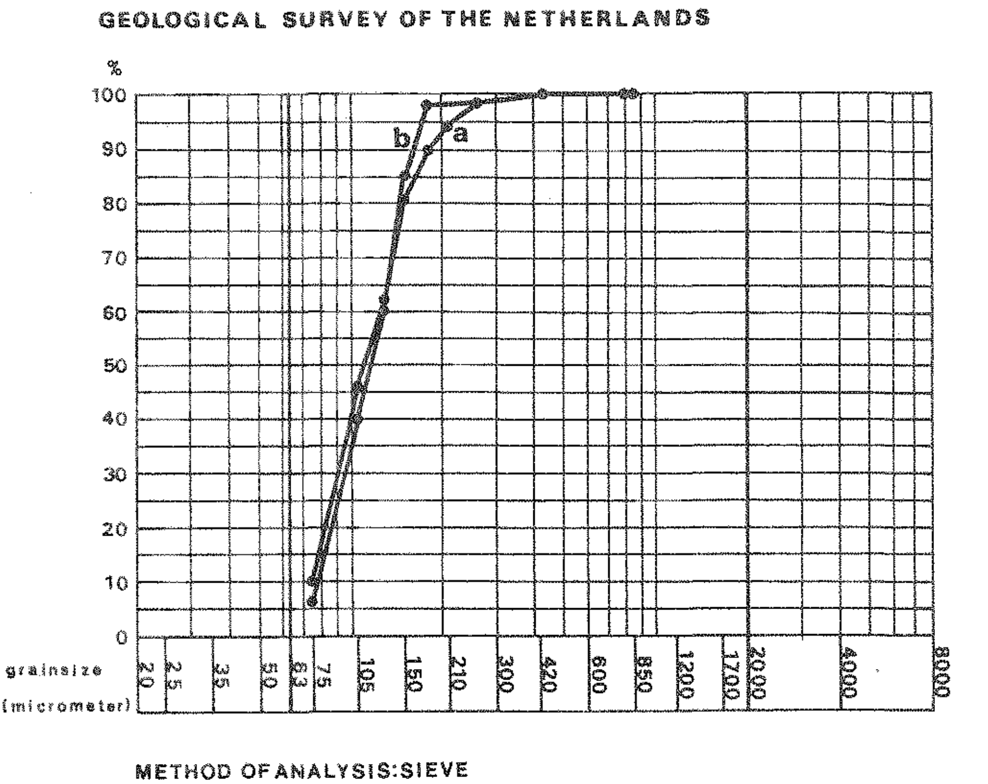


Fig. 64. Grain size analyses of the Well Ground Formation in boreholes F4-3 (a) and F4-5 (b).

ments. During the maximum extent of the ice fans were formed of which erosional remnants have been recorded (Fig. 66).

On seismic profiles at these locations in the southern part of block A15 and also in the north-eastern part of block A18 ridge-like structures have been observed resting on top of the Cleaver Bank Formation. The seismic characteristics of the structures point to a coarse-grained material. The overlying Dogger Bank Formation shows draped reflectors over this structure. The structures are interpreted as icings formed during the Saalian glaciation. It is however possible that they have been formed during the Late Weichselian glaciation (see Chapter 5.4.1).

6.4 Glaciolacustrine/marine deposits (Dogger Bank Formation)

6.4.1 Dutch sector

Most of the north-western part of the Dutch sector is covered by a sheet of stiff clay, the Dogger Bank Formation (Jeffery et al., 1989). The formation is named after the Dogger Bank and by which it is partly overlain.

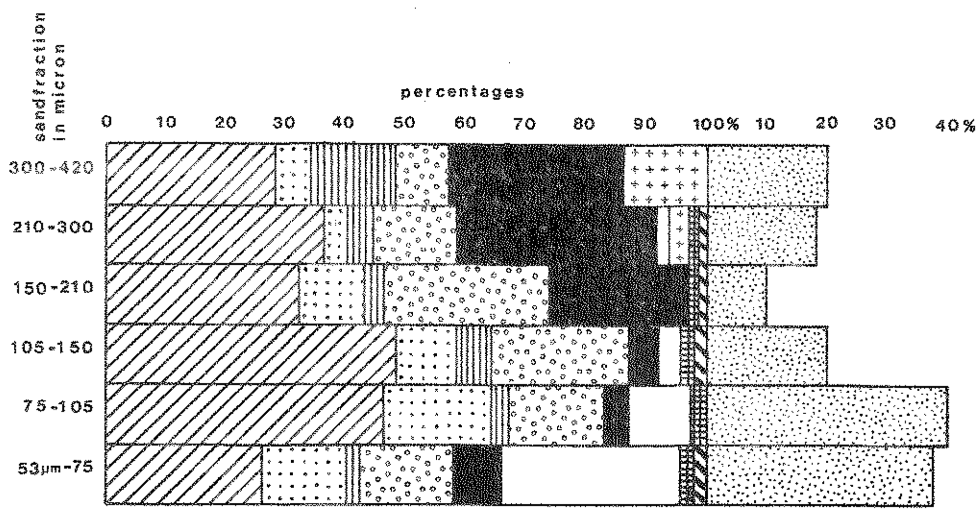


Fig. 65. Heavy mineral diagrams of the Well Ground Formation in block K1 (for legend see Fig. 45a p. 85) (after Dijkmans, 1981).

The formation consists of firm to stiff clay with silt laminae and lenses (Fig. 67). The formation appears to be mainly deposited in a glaciolacustrine, locally glaciomarine environment. It has been sampled in numerous boreholes and cores. Locally there is evidence for overlying patches of basal till.

Borehole A18-3 penetrated sediments consisting of firm grey clay rich in calcium carbonate. The deposits are overlain by Holocene marine sediments. Pollen analysis recorded a mixed Tertiary/Mesozoic assemblage in which the Tertiary component is dominant (Zagwijn, 1974). Similar pollen assemblages were found in this formation in boreholes E2-3 (Zagwijn, 1970b) and E3-5 (De Jong, 1987). Foraminiferal analysis on samples of the formation in borehole E2-3, between 64.80 m and 43 m below MSL, indicated a non-marine environment of deposition with a rich Mesozoic and Tertiary fossil fauna (Neele, 1985). The glaciolacustrine deposits in this borehole overlie about 6 m of periglacial deposits which contain a very high percentage of herb pollen, deposited during cold climatic conditions (Zagwijn, 1970b) (see Chapter 6.13). The sediments overlie the Elsterian Swarte Bank Formation (see Chapter 4.7).

In borehole E1-10 the formation, sampled between 44.40 m and 35.50 m below MSL, is underlain by the Cleaver Bank Formation and overlain by Holocene marine sediments. Pollen analysis show the same mixed Scandinavian/British assemblage as in the boreholes described above. Foraminiferal and mollusc analysis indicate a non-marine depositional environment (Neele, 1986; Sliggers & Meijer, 1987). In borehole E8-4, between 59.54 m and 48 m below MSL, the very stiff clay of the Dogger Bank Formation is underlain by marine Holsteinian sediments and overlain by Holocene marine deposits. Pollen analysis again showed the same British\Scandinavian assemblage. Foraminiferal analysis indicate a non-marine environment of deposition for the clay. The clay contains layers with a moderately

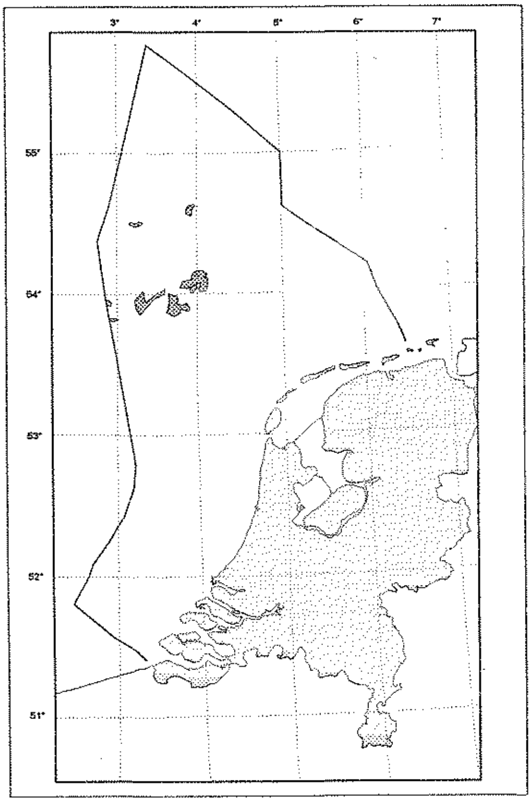


Fig. 66. Geometry of the Well Ground Formation below Holocene sediments. The depth to the top of the formation varies between 45 m and 50 m below MSL.

rich fauna with species like *Cassidulina reniforme, Ammonia beccarii, Buccella frigida, Elphidium excavatum f. clavata* and fossil Mesozoic species indicating a British origin for the sediments. It is not clear whether these layers were deposited in a marine environment or whether the foraminifera were reworked (Neele, 1986). The presence of fossil Mesozoic species tend to suggest that the deposit contains a reworked fauna.

South of appr. 54° 35'N the formation is predominantly overlain by till. North of this latitude the formation contains intercalations of fine gravel, regarded as ice-rafted debris (dropstones) and probably indicating deposition by floating ice (e.g. boreholes E1-10, E5-2, E6-1 and E8-4). X-ray photographs of samples 13 and 15 from borehole E1-10 show a homogeneous clay with an upward increase of matrix-supported angular fine gravel and probably indicating a closer proximity to ice (Fig. 68).

In the area where the formation underlies Holocene sediments the Dogger Bank Formation is locally covered by a thin layer of till suggesting an ice cover during a later phase. A thin section (No. 0.644) of the formation at a depth between 58.41 m and 58.30 m below MSL in borehole E8-4 was described by Van der Meer & Laban, (1990). From the microstructures, which indicate glacial shear, it was concluded that the clay was deposited as a basal (lodgement) till.

At several locations additional high quality cores were taken in 1994 in the Dogger Bank Formation allowing X-ray photography. The X-ray photograph of core E4-24 shows parallel and sub-parallel lamination with distorted beds possibly caused by slumping, but deformation by ice cannot not be excluded (Fig. 69a) core A18-16 shows a homogeneous deposit with faint sub-horizontal layers and lamination (Fig. 69b).

The Dogger Bank Formation extends over the northern K-blocks, the entire area of the A- and E-blocks and the western Fblocks. The depth to the top below MSL of the formation dips in an easterly direction from <40 m along the median line to >56 m on the eastern extent of the Dutch sector. The thickness varies between 4 m and 10 m in the south-west increasing towards the north and north-west to values of between 10 m and 20 m (Figs 70 and 71).

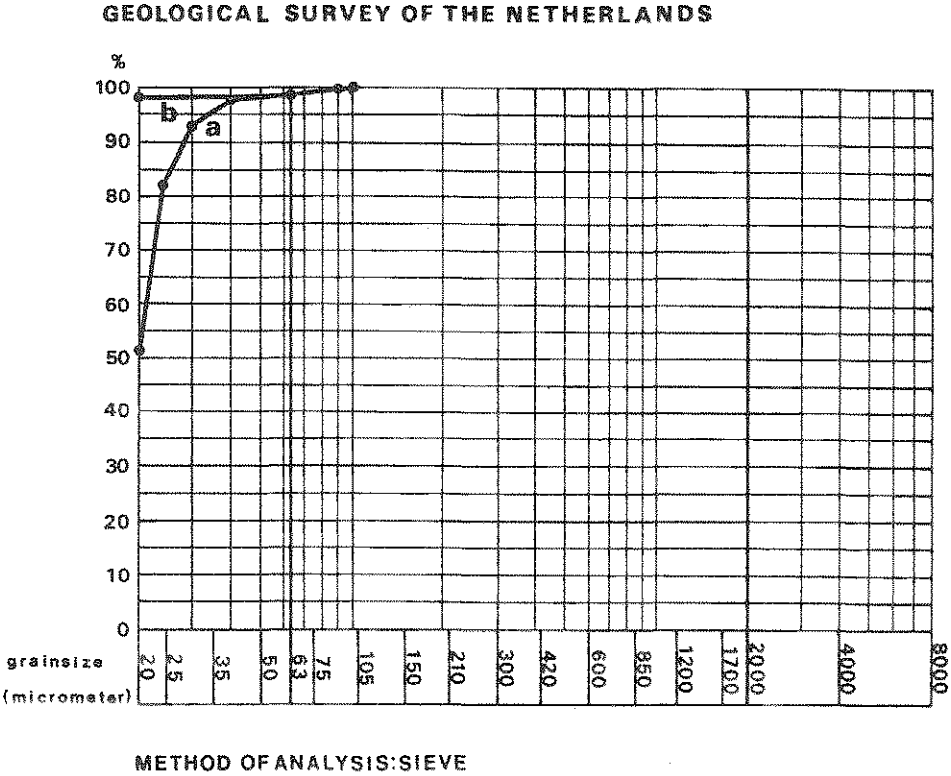


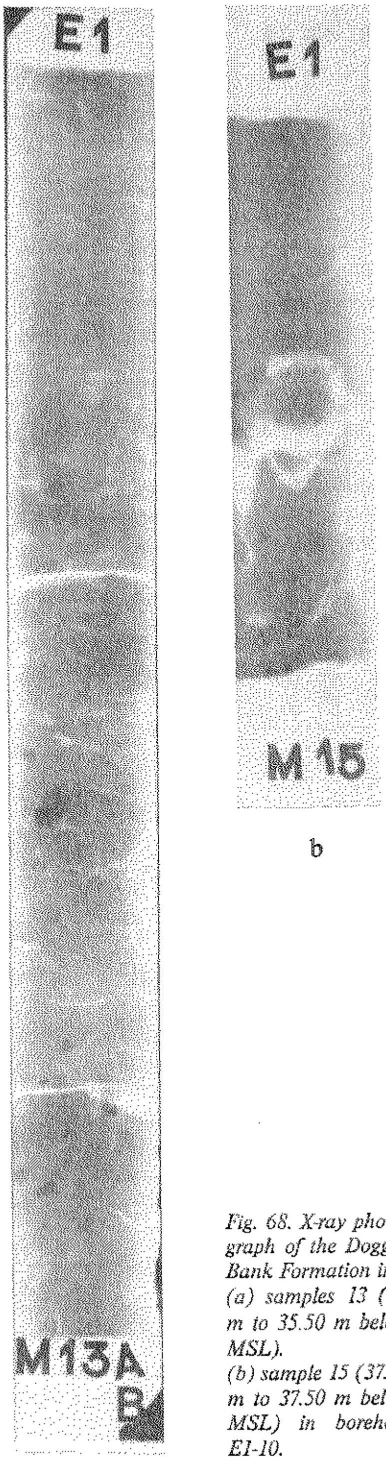
Fig. 67. Grain size analysis of the Dogger Bank Formation in boreholes F3-4 (a) and F4-5 (b).

Deposition initially took place by ice advancing from a westerly direction and then at a later phase from a more northerly direction. This is concluded from the direction of the axes of the subglacial channels (Fig. 82). In the south these channels show a mainly north-easterly direction while in the north a south-easterly direction predominates (see Chapter 6.5).

On the high resolution seismic profiles a subhorizontal acoustic lamination is locally present which, in the A-blocks, is sometimes wavy, possibly due to ice-pushing. The ice advanced from the north and overrode earlier glaciolacustrine sediments.

6.4.2 British sector

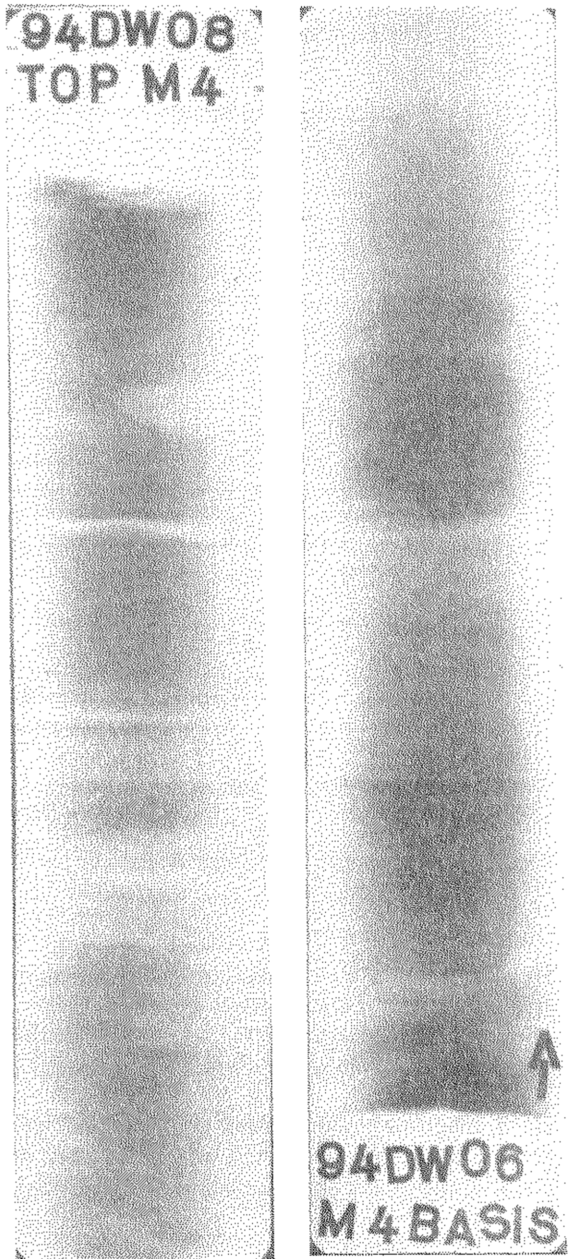
Glaciolacustrine sediments are widespread in the British sector between c. 54° 30'N and c. 55° 40'N. They consist mainly of clay-rich diamictons in which the pebbles are smaller, less numerous and less varied than in the till of the Bolders Bank Formation (see Chapter 6.7). The sediments generally show a well-developed stratification and lamination (Jeffery et al., 1991). According to Cameron et al. (1992) the Dogger Bank Formation in the British sector is the lateral equivalent of the Bolders Bank Formation (see Chapter 6.7).



a

b

Fig. 68. X-ray photograph of the Dogger Bank Formation in (a) samples 13 (35 m to 35.50 m below MSL). (b) sample 15 (37.10 m to 37.50 m below MSL) in borehole E1-10.



a

b

Fig. 69. X-ray photographs of the Dogger Bank Formation in (a) core E4-24 and (b) core A18-16 between 3 m and 3.50 m below sea bed showing parallel and subparallel laminae and locally indications of shearing due to glacial overriding.

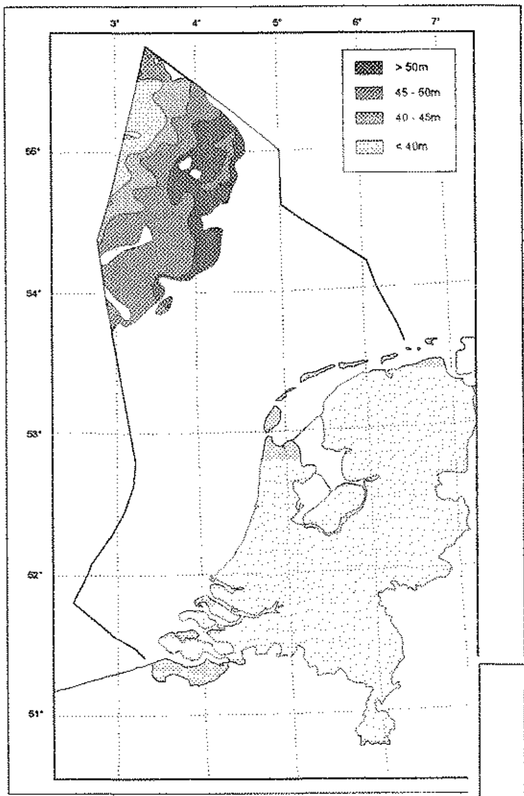
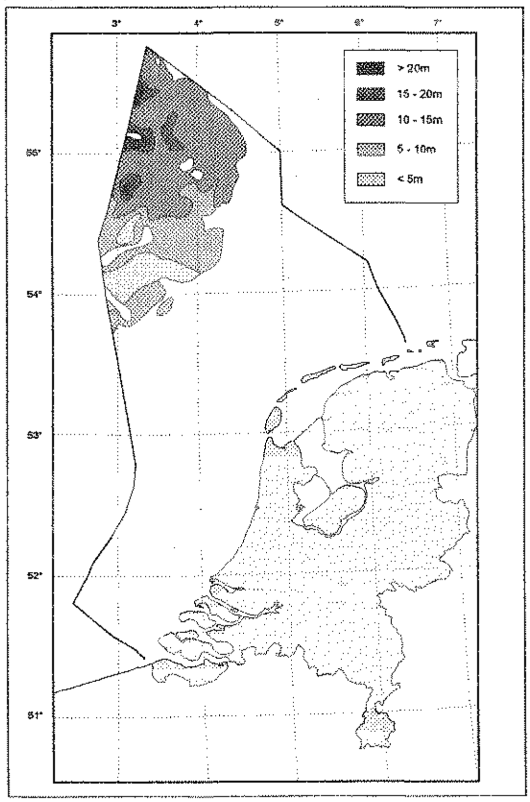


Fig. 70. The geometry and depth below MSL to the top of the Dogger Bank Formation.

Fig. 71. The geometry of the Dogger Bank Formation. Thickness in metres.

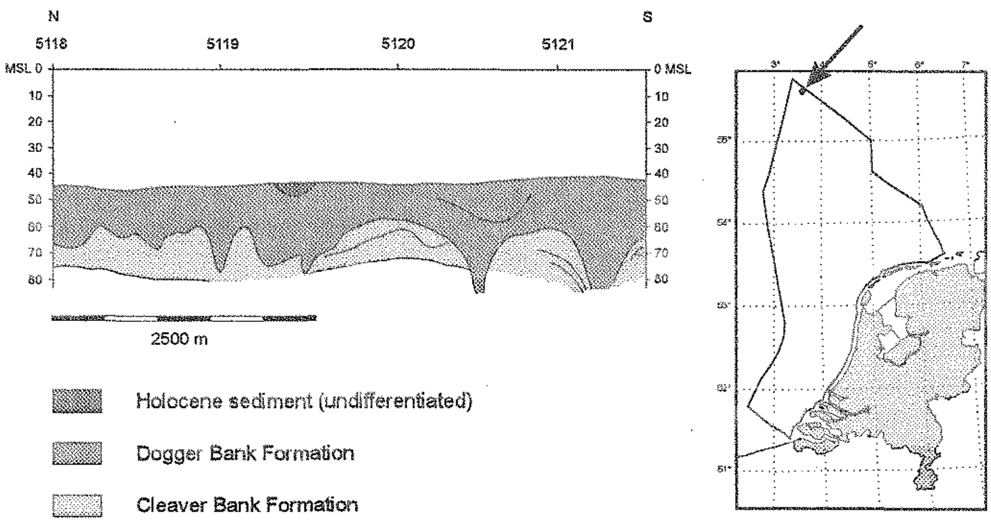


6.4.3 Danish sector

In three boreholes in the southern part of the Danish sector (Roar 41, Skjold 21 and Dan 31) a non-marine clay was interpreted as Weichselian by Knudsen (1985; 1986) based on the foraminifera present in both the overlying and underlying sediments. In borehole Roar 41 the deposits are overlain by Weichselian glaciomarine sediments and in the other two boreholes by Holocene sediments. The underlying marine sediments with shallow water foraminiferal faunas were dated as Eemian, presumably overlying Saalian or older glacial deposits. Amino acid analysis of benthic foraminifera of the underlying marine sediments also indicated an

Eemian age. Salomonson & Jensen (1994) described two other boreholes (Valdemar BH6 and BH89/7A) drilled north-west of the above in which the Weichselian and Eemian sediments were correlated using seismic profiles.
Thompson et al. (1992) determined the magnetic properties of borehole 89/7A in the Danish sector and interpreted Weichselian glaciomarine and glaciolacustrine sediments between 87 m and 55 m below MSL underlying Holocene and overlying Saalian and Eemian marine sediments.
South-west of borehole 89/7A, in borehole A9-9, in the Dutch sector, the Saalian glaciolacustrine sediments are present close to the sea bed and are overlain by Eemian marine sediments (Chapter 5.4). The Danish authors did not reconstruct or discuss the extent of the Weichselian ice sheet in the Danish sector. If their interpretations are correct, deposition of glaciolacustrine sediments in the Danish sector most probably took place by an ice sheet south-west of the Norwegian coast as envisaged by many previous workers like Woldstedt (1929) and Nesje & Sjerup (1988) (see Chapter 6.14).
In 1989 a high resolution seismic line was run over the Danish boreholes then passing through the German and into the Dutch sector. Back (1992) interpreted the seismic profiles and attempted to correlate the Dutch with the Danish boreholes. Due to bad resolution locally the correlation was however poor. Bertelsen (1972) investigated two boreholes in the southern part of the Danish sector (Nordsø A1 and A2) (see also Chapters 3.1 and 5.4), and close to the boreholes mentioned above. No evidence was found for Saalian and Weichselian glaciolacustrine deposits or for Holsteinian and Eemian marine sediments. It is however possible that the clayey interval between approximately 62 m and 48 m below MSL in the gamma ray log of borehole Nordsø A2, (regarded by the present author as possibly Saalian), is overlain by Weichselian glaciolacustrine clay. The gamma ray log indicates an increase of fine-grained sediments in the latter interval.

Fig. 72. Interpretation of a seismic profile through channels filled with the Volans Member of the Dogger Bank Formation in block A8.



6.5 Glaciolacustrine deposits (Dogger Bank Formation, Volans Member)

6.5.1 Dutch and British sectors

In the northernmost part of the Dutch A-blocks and in the adjoining British sector the Dogger Bank Formation, and locally even the underlying Cleaver Bank Formation, have been incised by a system of V-shaped channels varying in depth between 60 m and 80 m below MSL (water depth between 40 m and 42 m) (Fig. 72). The infill of the channels, sampled in the boreholes A8-5, A8-2 and A8-25, consisted of stiff greyish-brown clay with silt enclosures. The clay belongs to the Volans Member of the Dogger Bank Formation and can only be distinguished seismically (Jeffery et al., 1991).
The channels are probably formed subglacially by an ice advance from the north-west during the last phase of the glaciation. The greater thickness of the formation in this area is an indication both for ice advance in association with a high rate of deposition. The earlier sediments of the Dogger Bank and Cleaver Bank formations show wavy reflectors at several locations. This is probably the result of ice-pushing from the north-west. The area north-west of the channels infilled with the Volans Member, in the British sector, shows strong subglacial erosion (Jeffery et al., 1991). In this area and between a system of deeply incised channels the Lower to Middle Pleistocene Yarmouth Roads Formation underlies Holocene sediments. The subglacial channels in that area extend to a depth of about 200 m to 300 m below MSL.

6.6 Glaciomarine facies (Dogger Bank Formation)

6.6.1 Dutch sector

In the northern part of the Dutch sector borehole A12-2 was, according Koomen (1994), drilled on the edge of a depression in the top of the Pleistocene whose upper surface varies between 48 m and 43 m below MSL. The depression appears to be infilled with clay which on the seismic profiles is seen to be acoustically laminated. Samples of this sediment were collected from this borehole between 50.54 m and 41.42 m below MSL and consisted of a very stiff, dark grey clay locally with sand inclusions and shell fragments. Foraminiferal analysis recorded an arctic to boreal littoral fauna containing *Elphidium excavatum f. clavata, Buccella frigida, Nonion orbiculare* and *Cassidulina reniforme*. The Late Weichselian clay is underlain by sandy marine sediments of the Eem Formation. These sediments contain a 'warm' foraminiferal fauna in which species such as *Ammonium beccarii* and *Nonion germanicum* dominate (Fig. 73). The number of foraminifera in the clay is poor however probably indicating a relatively high sedimentation rate (Neele, 1988).

Little is known of the glacio-isostatic movement of the area just north of the Dogger Bank since the Late Weichselian, but it is most probable that this depression was connected with the Late Weichselian shoreline north of the Dogger Bank dated at 10,300 BP as hypothetically suggested by Jelgersma (1979) or at 10,000 BP as suggested by Lambeck (1995). The ice sheet in the area of the present Dogger Bank, however, must have had a greater thickness considering the deep subglacial erosion (Chapter 6.11.1) (Wingfield, 1989; Jeffery et al., 1990) that took place than the ice sheet in the area south of the Dogger Bank (Lambeck, pers. comm.). Due to the ice loading crustal subsidence probably took place causing a depression in which the rising sea-level entered.

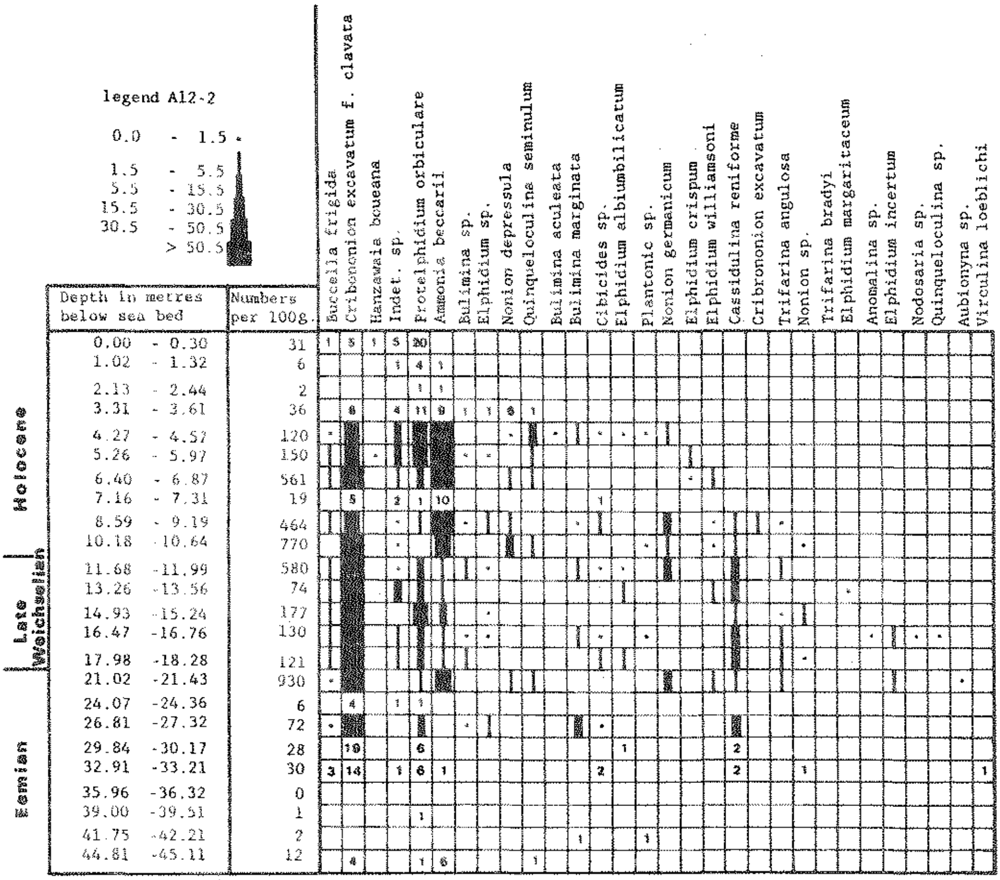


Fig. 73. Foraminiferal analysis of the glaciomarine clay in borehole A12-2 (after Neele, 1988).

6.6.2 Danish sector and Jutland (Denmark)

According to Knudsen (1994) the deglaciation of northern Jutland was reflected by the re-establishment of marine conditions after the main glaciation around 15,000 BP.
Late Weichselian and Late Weichselian marine sediments from northern Jutland were described by Petersen (1984; 1985). These sediments, deposited in a shallow marine environment, contained a boreal to arctic mollusc community characterized by *Zirphaea crispata*. ^{14}C-datings of molluscs indicate ages of between 14,000 and 15,000 BP. Between 13,000 and 14,000 BP the highest sea-level of 60 m above present day level is thought to have been reached. Mollusc species typifying water depths of more than 20 m such as *Hiatella arctica, Mya truncata, Macoma torelli, Portlandia arctica* are present. Knudsen (1978) recorded foraminifera species such as *Elphidium excavatum f. clavata, Cassidulina reniforme, Buccella frigida, Nonion orbiculare* indicating an arctic environment. Further climatic amelioration between 13,000 and 12,000 BP is indicated by the occurrence of mollusc species such as *Mytilus edulis, Macoma baltica* and *Arctica islandica*. During the Late Dryas Stadial sea-level fell again, according to Petersen (1985).

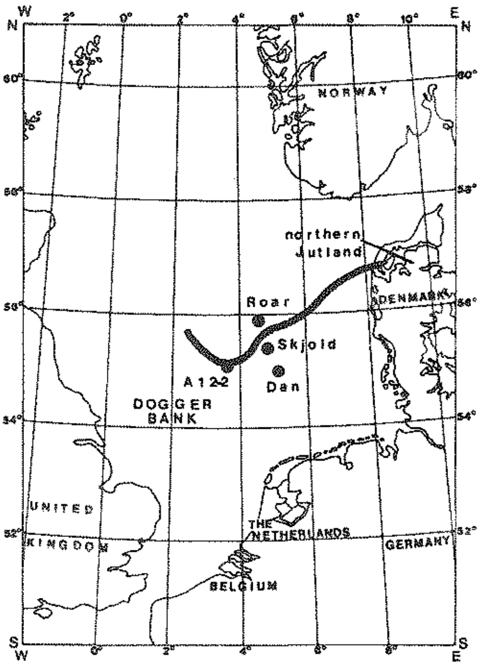


Fig. 74. Locations of boreholes with Late Weichselian glaciomarine sediments in the Danish and Dutch sectors of the North Sea and northern Jutland, Denmark (after Koomen, 1994).

In the Danish sector of the North Sea the arctic to boreal foraminiferal fauna found in borehole Roar 41 was interpreted by Knudsen (1985) as probably indicative of Late Weichselian glaciomarine clay. The deposits overlie glaciolacustrine clay and marine sandy sediments. In the Danish sector the latter were dated as Eemian (Sejrup & Knudsen, 1993) by amino acid analyses. The foraminiferal fauna of borehole Roar 41 is probably comparable with the foraminiferal fauna found in borehole A12-2 in the northernmost part of the Dutch sector (Fig. 74).

6.6.3 British sector

In the British sector near the northern extension of the Dogger Bank Formation, and north of 55°N, a transition takes place into a glaciomarine depositional environment. In this area reworked pre-Pleistocene dinoflagellate cysts in the upper layers are mixed with autochthonous cysts indicative of severe, cold, open-water, marine conditions (Cameron et al., 1992).

North of 56°N in the British sector the Late Weichselian/Early Holocene Forth Formation underlies Holocene open marine sediments. The Fitzroy Member of this formation contains Weichselian soft, silty clays with dropstones which were deposited in a marine environment. They are present also along the median line between the British and Danish sectors and also along the northern boundary of the British-Dutch Dogger sheet (Fyfe, 1986, Jeffery et al., 1990).

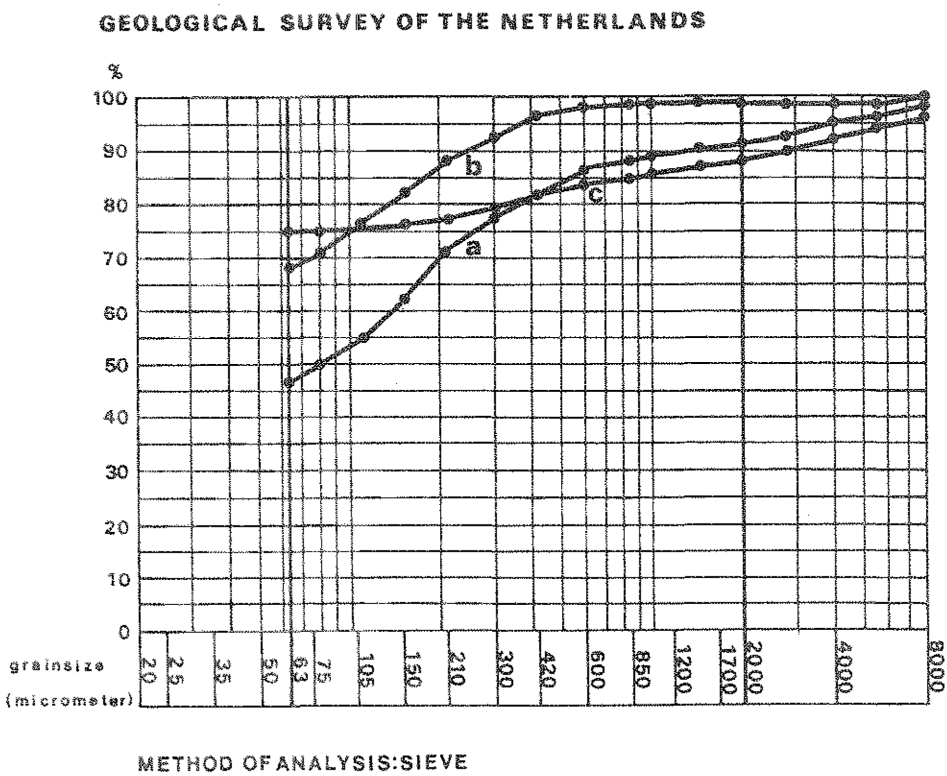
6.7 Boldersbank Formation (till)

Veenstra (1965) collected 40 cores and a number of grab samples at the south-eastern margin of the Dogger Bank (between 53° 50'N and 54° 50'N/ 2°E and 4°E). From the sediments sampled Veenstra concluded that the Dogger Bank is underlain by till which was presumably deposited during the Weichselian glaciation. Pollen analysis on grab sample 146 recorded abundant Carboniferous and Jurassic spores indicating a British provenance (Zagwijn & Veenstra, 1966). Oele (1969) sampled tills in two boreholes (E2-1 between 39.31 m and 39.20 m below MSL, and E8-3 between 45.10 m and 44.65 m below MSL) east of the Dogger Bank. He suggested, based on pollen analysis indicating a high percentage Tertiary pollen (Zagwijn & De Jong, 1969), that the tills were of Scandinavian origin. Donovan (1973) sampled tills at three locations around and to the east of the Silver Pit (between 53° 20'N/0° 30'E and 53° 45'N/0° 50'E) and correlated them with the Late Weichselian Purple and Drab Tills of the coastal till sequence of East Yorkshire.
Cameron et al. (1986); Jeffery et. al. (1989); Tappin (1991) and Laban et al. (1995a) map-

ped this till from the British east coast, south of Skegness in Lincolnshire, in a north-easterly direction as far as 4° 10'E in the Dutch sector.
In the Dutch sector the till has been sampled in numerous boreholes and cores and consists predominantly of brown to greenish-grey, stiff, sandy clay (<63 μm varying from 46.8 to 75%) with mainly matrix-supported crystalline and chalk gravel (varying from 3 to >10%) together with a high percentage of flint (Fig. 75); sand layers and laminae are locally present. The till is rich in calcium carbonate. The formation is named after the Bolders Bank in the British sector (54° 20'N/01° 40'E).

In borehole K1-108 the till was sampled between 48.10 m and 46.10 m below MSL. The till is underlain by fluvioglacial sand of the Well Ground Formation and is overlain by 3 m of gravelly Holocene deposits. Heavy mineral analysis has been carried out by Dijkmans (1981) on samples of the till from this borehole and also on two other boreholes notably D18-33 between 45.90 m and 45.30 m below MSL and E16-39 between 46.70 m and 38.90 m below MSL from the area between the Botney Cut and the Cleaver Bank.
Dijkmans analyzed the fraction between 53 μm and 500 μm and concluded that the assemblages differ substantially from each other. Dijkmans also compared the analyses of the North Sea samples with analyses carried out on samples of the Weichselian Drab Till and

Fig. 75. Grain size analyses of the Bolders Bank Formation of in boreholes K1-13 (a), E5-2 (b) and E6-1 (c).



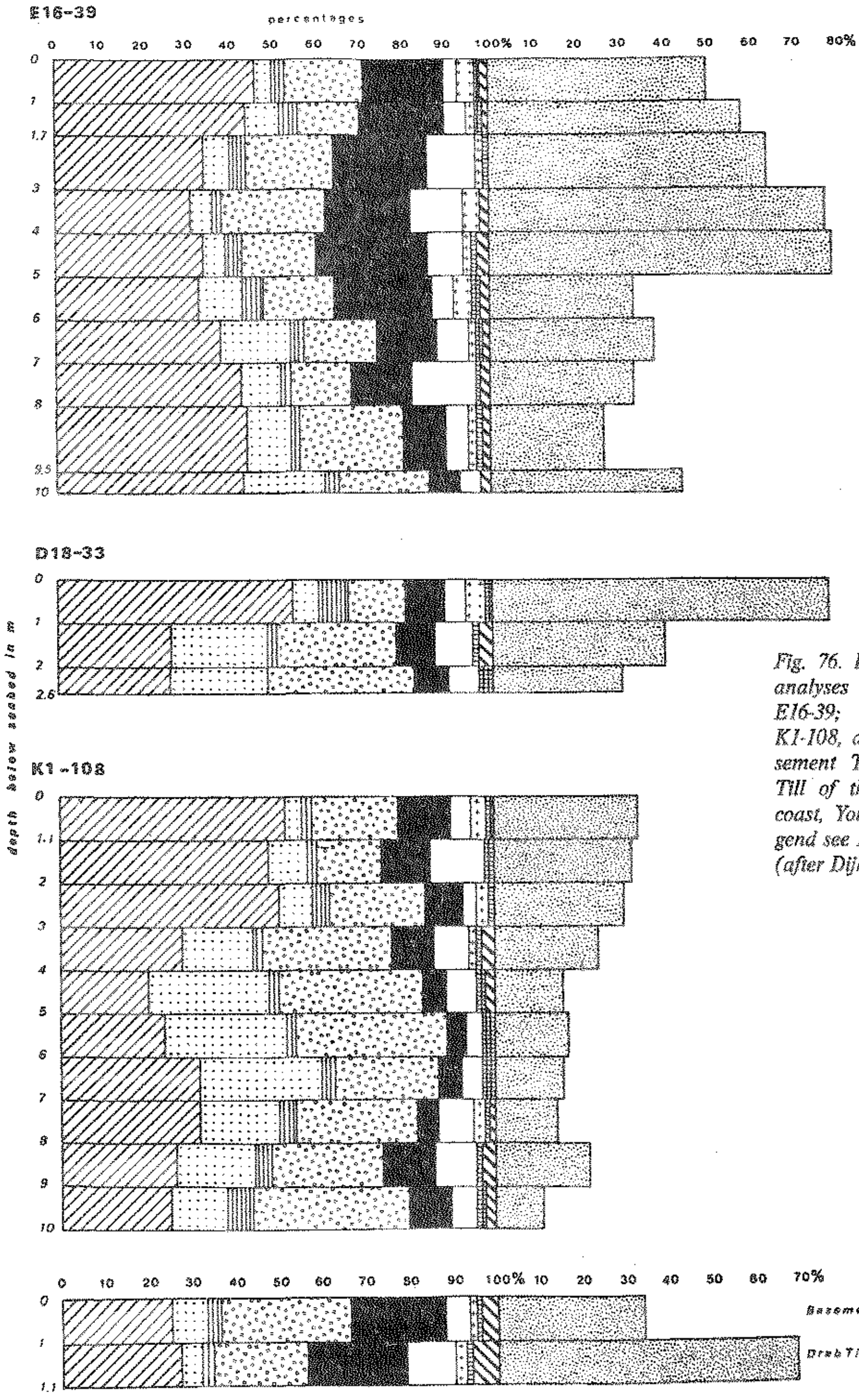


Fig. 76. Heavy mineral analyses of boreholes E16-39; D18-33 and K1-108, and of the Basement Till and Drab Till of the Holderness coast, Yorkshire (for legend see Fig. 45a p. 85) (after Dijkmans, 1981).

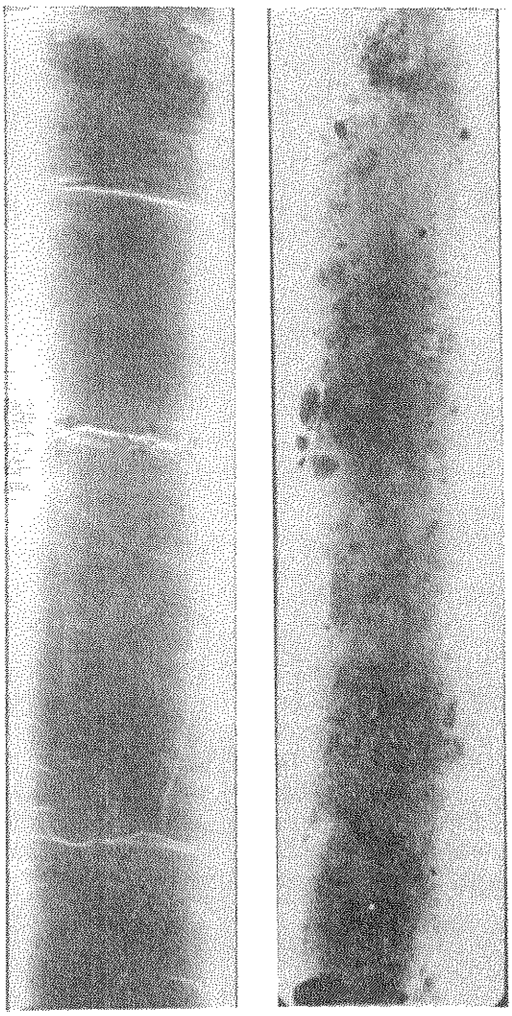
the "Wolstonian" Basement Till of Holderness (Fig. 76). He concluded that the mineral assemblages of the North Sea tills resemble those of the British tills and that they include a high percentage of garnet. The pyroxene percentage in the North Sea tills is however lower than that in the Holderness tills. These differences could be caused by the long transport distance between the North Sea tills and those of the Holderness coast.

Besides the heavy mineral analyses Dijkmans (1981) also analyzed the gravel content in tills of boreholes D18-32 (between 45.40 m and 43.40 m below MSL), D18-33 (between 45.90 m and 45.30 m below MSL), J3-29 between 42.20 m and 40.10 m below MSL), and K1-106 (between 44.10 m and 40.70 m below MSL) which were drilled in the same area south-east of the Dogger Bank. He compared the results with analyses of the Holderness tills and concluded that the differences with the North Sea tills are small and that the gravel resembles the gravel of the Late Weichselian Skipsea Till from the Holderness coast. Gravel of Scandinavian provenance from Saalian tills sampled in the coastal area of The Netherlands is by contrast very different, e.g. the high porphyry content is unknown from the Scandinavian tills in The Netherlands. Similar studies as those of Dijkmans have been carried out on tills of several other cores and boreholes. Core E4-1 (between 40.93 and 40.78 m below MSL) and borehole E16-3 (between 41.20 m and 40.20 m below MSL) recorded an association of dark brown porphyries with white phenocrysts; these are not present in the Saalian tills in The Netherlands and are most probably of British provenance (Zandstra, 1969c, 1973).

Thin sections have been made of the tills of core K1-13 from a depth of between 37.67 m and 37.62 m below MSL (thin section No. 0.642) and of borehole E8-4 from a depth of between 52.01 m and 51.90 m below MSL (thin section No. 0.643). Both tills may possibly be interpreted as flow tills (Van der Meer & Laban, 1990). Additional thin sections of samples of the formation have been made from cores taken near the Cleaver Bank. The interpretation of samples of flow tills (thin sections No. Mi. 838 and No. Mi. 845) from cores E16-542 (between 38.75 m and 38.90 m below MSL) and E16-551 (between 42.38 m and 42.24 m below MSL) shows strong disturbance with a linear blocky arrangement indicating microfaulting caused by glacial overriding (Van der Meer, 1995).

An X-ray photograph of core E16-551 (between 2.50 m and 3 m below sea bed), taken on the eastern slope of an ice-pushed knob, shows a transition from a well laminated till with fine matrix-supported gravel to a laminated till locally with thin layers of fine gravel (Fig. 77a). The X-ray photograph of core E16-557 (between 2.50 m and 3 m below sea bed) which was taken on the western slope of the same ice-pushed knob (see Chapter 6.10), shows no lamination or layering, and is rich in matrix-supported, subrounded to angular gravel (Fig. 77b).

On seismic profiles the formation has a chaotic to poorly ordered internal seismic reflector configuration. In areas with thicknesses of <2 m no reflectors are observed on the seismic profiles. Locally it is difficult to distinguish the formation seismically from the Dogger Bank Formation. This is due to the fact that the till contains only fine gravel which does not cause hyperbolic reflectors.
The depth to the top of the formation varies between 40 m and 50 m below MSL and is strongly undulating thus making it difficult or impossible to draw contour lines. The thickness of the formation varies between less than 2 m to 6 m.



a b

Fig. 77. X-ray photographs of the Bolders Bank Formation in cores E16-551 (a) with only some fine gravel and faint parallel lamination probably indicating a waterlain till and E16557 (b) rich in matrix-supported gravel.

Indications for Scandinavian tills in the eastern part of the North Sea were reported by Foged (1987) in the northwestern part of the Danish sector where the topography and the presence of stones and blocks may reflect Weichselian till.

6.8 Glacial gravel (Indefatigable Grounds Formation)

In the British sector west and south of the Dogger Bank extensive areas with medium- to coarse-grained gravelly sand are present and overlie till. In the Dutch sector the deposits are found around the Botney Cut and the Cleaver Bank. The deposits are referred to the Indefatigable Grounds Formation (Harrison et al., 1987). The gravel content varies between 30% and approximately 70%. The thickness of the layer ranges between 0.1 m in areas with a flat sea bed to >2 m on top of and around the ice-pushed knobs (Laban, 1982, 1984; Jeffery et al., 1989). Side-scan sonar images indicate the occurrence of blocks of more than 1 m in diameter on the sea bed. During sampling programmes in this area, blocks with a diameter of up to 0.7 m have been collected. North of this gravel field small areas with thin gravelly layers are locally present.

Pratje (1951) mapped the gravel and coarse sand occurrences on the sea bed from fishery charts together with additional data from grab samples and echo soundings in an attempt to reconstruct the most probable limits of the Scandinavian Saalian and Weichselian ice sheets. Based on the heavy mineral investigations of Baak (1936), Pratje concluded that the gravel south-west and west of the Dogger Bank was of British origin. Pratje regarded the gravel occurrences as end moraines. Other workers on the gravels included Borley (1923) and Berthois (1957) who both collected gravel samples near the Dogger Bank. They recorded basalt, gneiss, feldspar, limestone, porphyritic andesite, granite, rhyolite, andesite, schist, quartzite, sandstone and flint. According to Borley the gravel was derived from stone banks near the British coast the material of which had been transported by wave action. Borley drew several maps with, respectively, the distribution of silt (0-0.09 mm), fine (0.1-0.49 mm), medium (0.5-0.9 mm) and coarse (1.0-1.49

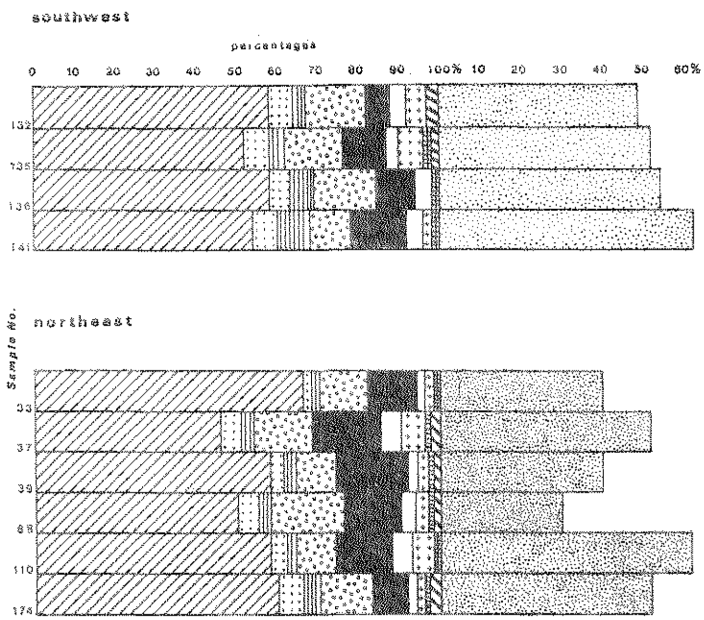


Fig. 78. Heavy mineral analyses of superficial samples of the overlying sand of the Bolders Bank Formation in the area south-west and north-west of the Botney Cut (for legend see Fig. 45a p. 85) (after Dijkmans, 1981).

mm) sand. The gravel was classified into fine (1.5-2.4 mm), medium (2.5-4.9 mm), coarse (5.0-9.9 mm), very coarse (10.0-14.9 mm) gravel and stone (>15 mm) fractions. In the area between the Botney Cut and the Cleaver Bank no gravel was shown, only medium sand. Veenstra (1965) collected 40 samples around and on both the Dogger and Cleaver banks. He mapped areas with coarse sand with shell debris, gravel and also boulder clay locally. According to Veenstra the most important components are sandstone, quartzite, flint, chalk, limestone, small porphyries and other crystalline fragments. Veenstra concluded that the gravel was transported by Weichselian ice of British provenance.

Petrological analyses on the gravel carried out by Dijkmans (1981) and Zandstra (1974) show evidence that the gravel association is comparable to that determined from samples collected from the underlying till (see Chapter 6.7). During earlier surveys in the area about 400 superficial samples were collected and described. Heavy mineral analyses on sand of the superficial sediments show similarity with analyses of the underlying till (Fig. 78).
Of particular significance is the fact that no ventifacts have been recorded from thousands of gravel fragments and blocks (Laban, 1982, 1984).

Most of the gravel has been reworked and redeposited by the action of strong tidal currents in this area during recent times. Side-scan sonar images show the occurrence of small scale ripples between overlying sand ribbons. According to observations by divers the ripples are up to 0.15 m in amplitude and consist of gravelly sand.

6.9 Tongue-shaped valley

Tongue-shaped basins, similar to Saalian examples in both The Netherlands and in the south-eastern part of the Dutch sector, have not been found in the sediments of the Late

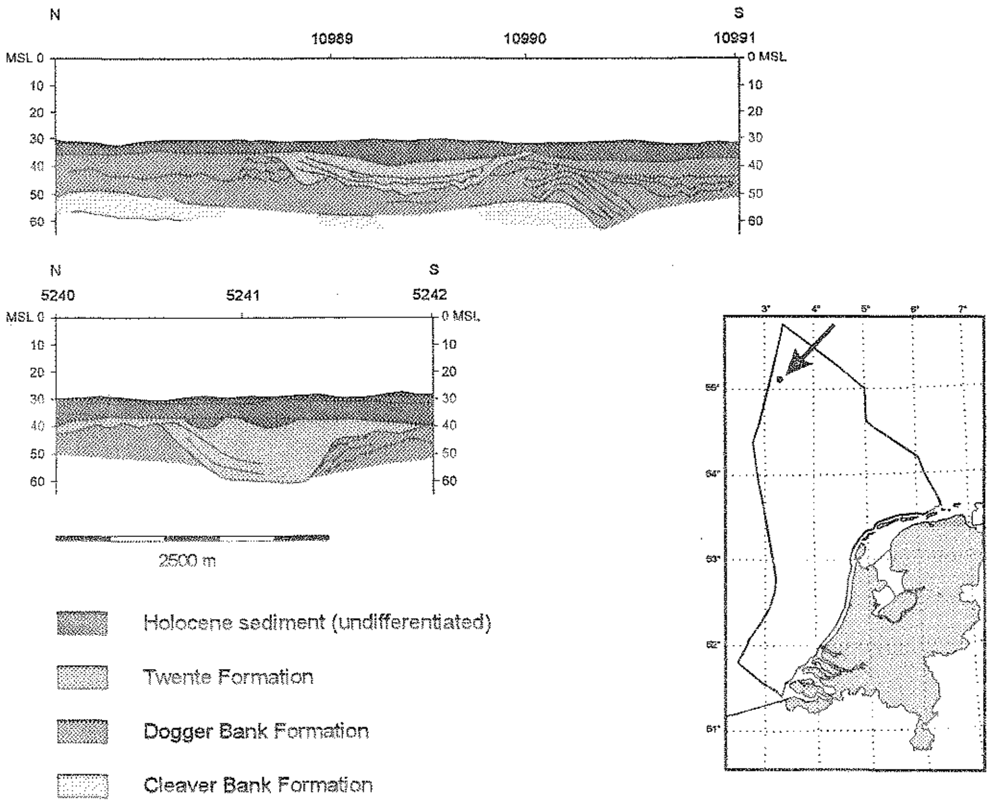


Fig. 79. A. Interpretation of a seismic profile over the western part of the tongue-shaped valley in block A16 showing an irregular base and deformation structures. B. The deeper part of the above valley in the south-east part of block A16.

Weichselian glaciation. At only one location in the northern part of the Dutch sector an isolated basin has been recorded. The basin has a length of approximately 13 km, is 2 to 4 km wide and has an east to south-east direction. The depth below sea bed ranges from 10 m in the west to 24 m at its termination in the south-east. In the western, shallow, part of the basin the base shows an irregular pattern, which suggests an initial subglacial scouring of the valley and a subsequent infill with deformation structures along the margins caused by pushing of the ice. The infill is draped over an irregular base (Fig. 79).

6.10 Ice-pushed knobs and deformation structures

Between the Botney Cut and the Cleaver Bank a series of more or less north-south trending, up to 13 m high, knobs are found. Several cores taken in the knobs showed that they are made up of the same till as sampled around the knobs (Laban, 1982, 1984) (Fig. 80). They appear to represent ice-pushed structures. In contrast, the east-west trending Cleaver Bank is built up of marine sand and was most probably formed during the Holocene transgression.

Deformation structures caused by ice-pushing are present along the margins of the valley discussed in Chapter 6.9 above and also in the northern part of the Dutch sector where

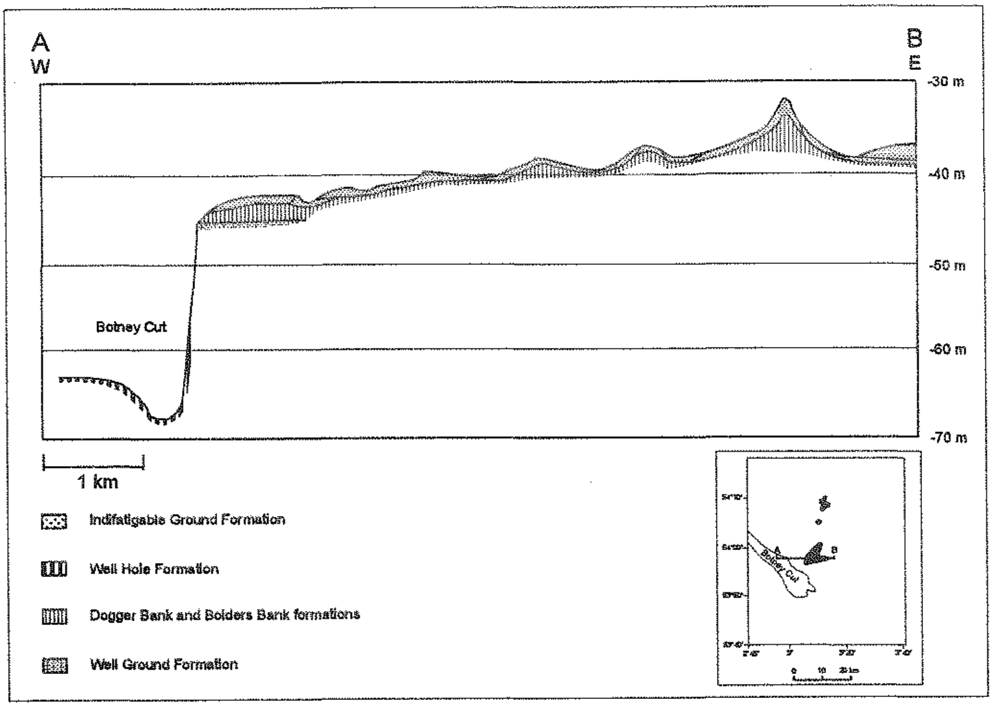


Fig. 80. A. Ice-pushed knobs between the Botney Cut and the Cleaver Bank. B. Cross section (A-B) from the northern margin of the Botney Cut through the knobs.

the Saalian Cleaver Bank Formation and the Dogger Bank Formation show wavy reflectors (Fig. 81).

6.11 Subglacial valleys

In this chapter depressions will be discussed which are formed underneath the ice sheet and which are named valleys by most authors although Wingfield (1989) uses the term glacial incisions. The present author while using the term valleys considers that this term can be applied where different types of genesis of depressions may be involved.

6.11.1 British sector

Valentin, (1955), Flinn (1967) and Donovan (1973) discussed closed V-shaped valleys west, north-west and north of the Dogger Bank. These included the Silver Pit, Well Hole, Markhams Hole, Sole Pit and Devils Hole and it was suggested that they must have been formed initially by meltwater escaping under pressure during the last glaciation.

Dingle (1971) studying seismic profiles run along the Northumberland coast, concluded that the 150 m to 200 m deep, narrow and steep-sided U- or V-shaped valleys, were not produced under subaerial conditions because it implied a glacio-eustatic sea level lowering of >250 m. From the association of physiography and associated sediments he suggested a genesis by subglacial erosion.

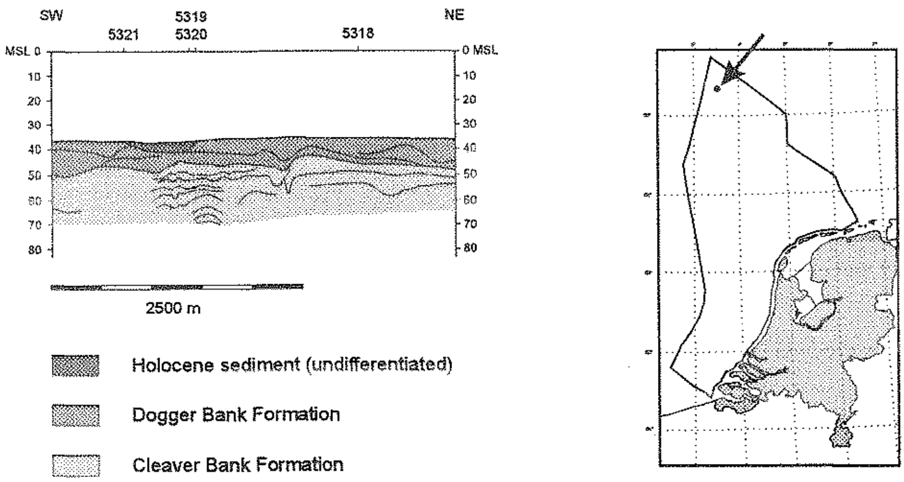


Fig. 81. Interpretation of a seismic profile showing wavy reflectors in the Cleaver Bank and Dogger Bank formations in block A8 due to ice-pushing.

Holmes (1977) suggested that the buried channels in the Central North Sea may have been eroded by post-glacial fluvial activity.
Long & Stoker (1986a, 1986b) described asymmetric open valleys in the central North Sea which have steep north-facing and shallow south-facing slopes. The valleys are closed at both ends and vary in width between 0.5 km and 3 km. The valleys are up to 40 km long, their base is undulating and lies at a depth of up to 200 m below sea-level (150 m below sea bed). The valleys are usually straight, but sometimes sinusoidal. The longitudinal slope angle varies between >20° to less than 2°. The valleys have been regarded as subglacially formed by several authors (Donovan, 1973; Flinn, 1978) or by tidal scouring by others (Thompson et al., 1977). All authors regard the asymmetry as the result of the valley flanks slumping during periglacial conditions. Most workers also consider that while some valleys were formed subglacially, the majority were probably formed by fluvial processes with their profiles subsequently becoming accentuated by catastrophic meltwater discharges both from ice-dammed and intra-ice lakes as well as by annual release of glacial meltwater from the ice front. The channels are thought to range from Middle to Late Pleistocene in age.

Balson (1994) is of the opinion that for several of the valleys in the southern part of the British sector which reach depths of 95 m below MSL, there is no evidence for a Weichselian infill and for subglacial genesis of the valleys. Seismic profiling showed that some of the valleys, as, for example, the Inner Silver Pit, the Cole Pit and Sole Pit, contain only some post-incision sediments and that the base of the valleys are resting on Pleistocene and locally pre-Quaternary formations. Cores penetrating to the base of the valleys recorded only Holocene sediments. Balson has suggested therefore a genesis by marine scouring during the Early Holocene transgression as was suggested earlier by Donovan (1965).

In the British sector north of the Dogger Bank, a dense pattern of braided subglacial valleys is eroded into the Early and Middle Pleistocene formations (Jeffery et al., 1991). Wingfield (1990) identified twelve separate incisions between 2 km and 5 km wide, up to 25 km long

and with a depth of between 150 m and 450 m below MSL. The infill, as described by Wingfield, partly resembles that of the Elsterian valleys and the Botney Cut (Cameron et al., 1986). A chaotic infill forms the basal part; sometimes it includes the entire infill and is overlain by draped stratified sediments. The infill in the upper part of the valleys however differs from their Elsterian and Weichselian counterparts in that they are cross-stratified according to Wingfield. The cross-cut reflectors vary in length between <2 m to 25 m. The uppermost sediments mainly consist of thin beds with a variable seismic character.

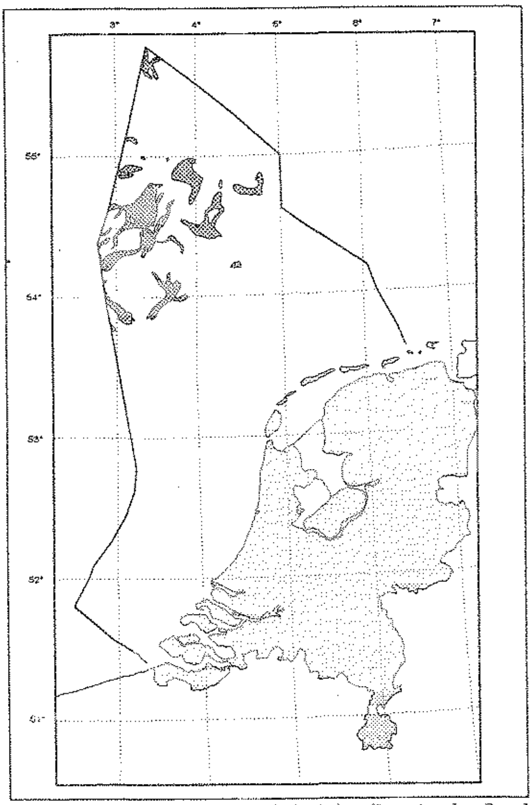


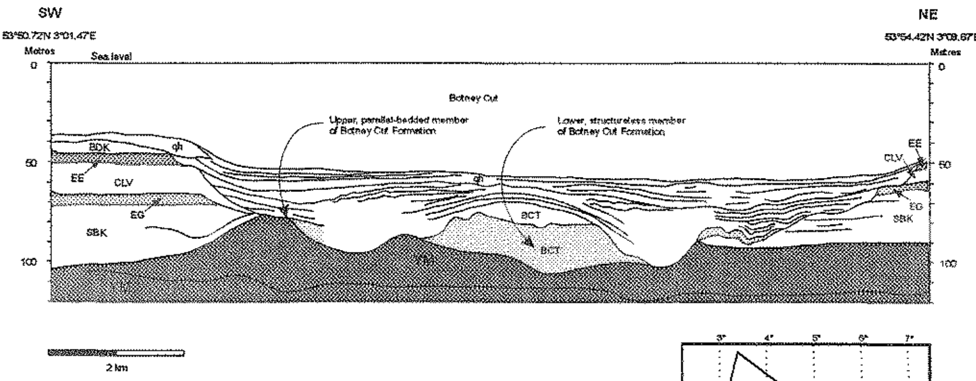
Fig. 82. The Weichselian subglacial valleys in the Dutch sector of the North Sea.

6.11.2 Dutch sector

In the Dutch sector a pattern of braided and isolated valleys have been eroded into and through the Bolders Bank and Dogger Bank formations. Erosional remnants of both formations are locally present in the valleys (Jeffery et al., 1989). Three main valley directions are present, south-east (e.g. the Botney Cut), north-east, mainly between 54°N and 55°N, and south-east, in the most northern part of the Dutch sector (see Chapter 6.5). The depth of the valleys range between 50 m to 100 m below MSL and have a width of between <1 km and appr. 10 km (Fig. 82). The base of the valleys is irregular. Locally, up to 40 km wide, saucer-shaped depressions are also present. Along the eastern margin of the maximum extent of the ice sheet the subglacial valleys sometimes continue as proglacial valleys.
Almost all valleys are buried. The infill consists partly of soft meltwater clays at the base (see Chapter 6.12) overlain by Holocene channel deposits. The Botney Cut however is partly open. The base of the valley locally reaches to a depth of 100 m below MSL and is filled to a depth of between 50 and 70 m below MSL. The water depth of the surrounding area is appr. 40 m (Fig. 83). North of the Botney Cut, in block D18, another partly open valley has been observed on the seismic profiles. This valley is narrow, about 1 km wide, and the base lies at 68 m below MSL. The valley is infilled to 16 m below the surrounding sea bed (Fig. 84).

6.11.3 Onshore valleys

Onshore in Denmark subglacial valleys of Weichselian age have also been found mainly eroded into older valleys of Elsterian and Saalian age (Sjörring, 1979). In northern Ger-



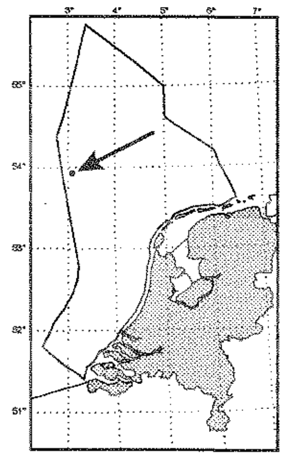
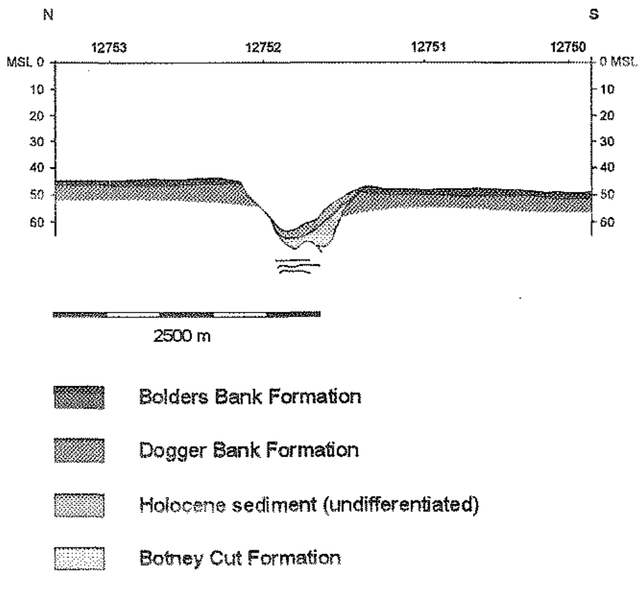
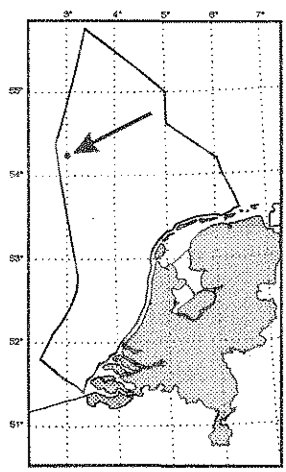


Fig. 83. An interpretation of a seismic profile across the Botney Cut
YM = Yarmouth Roads Formation
SBK = Swarte Bank Formation
EG = Egmond Ground Formation
CLV = Cleaver Bank Formation
EE = Eem Formation
BDK = Bolders Bank Formation
BCT = Botney Cut Formation
qh = Holocene
(Cameron et al., 1986).

Fig. 84. Interpretation of a seismic profile over a partly open (subglacial?) Late Weichselian channel north of the Botney Cut in block D12.





many near Hamburg a braided pattern of valleys only 5 m to 10 m deep has been found (Grube, 1969, 1979, 1983).

6.12 Subglacial channel infills (Botney Cut Formation)

6.12.1 Dutch sector

The infill of the partly buried subglacial valley of the Botney Cut consists at the base of coarse gravelly sediments which have been sampled as well as having been observed on seismic profiles. During a CPT at the base of a valley in Dutch block D15, and located to the north of the Botney Cut, a gravelly layer was encountered overlain by soft sediments (Joustra, pers. comm.). Boreholes indicate that the coarse infill is overlain by greyish-brown, soft to stiff, silty clay. On seismic profiles draped structures are observed over the coarse basal infill. The soft clay is covered by Holocene silty sand and clay. The other valleys, north-east of the Botney Cut, are mainly filled with a soft silty clay, diamictons and sandy sediments overlain by Holocene channel deposits. In borehole E4-10, drilled in a narrow north-east/south-west trending valley, the formation, sampled between 50.60 m and 44 m below MSL, consisted of brownish-grey silty clay locally with sand laminae; between 50 m and 49 m below MSL a layer of medium sand with some very fine gravel is present. The formation is overlain by 2 m of Holocene marine sand and clay deposits. In borehole E7-5, between 43.70 m and 40.70 m below MSL, the upper part of the infill consists of very fine, slightly silty, micaceous sand with some fine gravel overlain by 1.70 m of Holocene marine sand. In borehole E8-13 the upper part of the infill consists of fine sand with some flint and crystalline gravel underlying 7 m of Holocene marine deposits. In borehole E11-4 the Botney Cut Formation has been sampled between 45.20 m and 44.20 m below MSL and consists of soft grey, slightly sandy clay. The formation is overlain by 9 m of Holocene deposits. At the base of the Holocene an 0.1 m thick layer of peat has been sampled overlain by 1 m dark grey clay and 8 m of very fine marine sand. Pollen analysis on the clay of the Botney Cut Formation in this borehole recorded an association containing a high percentage of *Populus sp.* (13%) and dated Early Holocene (Preboreal). No marine indicators were found. The sediments contain 3.5% of Hystrichosphaeridae and 4% of spores derived from older formations (De Jong, 1974).

6.12.2 British sector

The infill of the 150 m to 450 m deep valleys described from the British sector are also formed of Botney Cut Formation deposits. In some of the valleys the basal member comprises a stiff reddish-brown diamicton which resembles the Bolders Bank Formation (Cameron et al., 1992). On the north-east coast near Sunderland a 75 km long, 15 km wide and up to 80 m deep trough is filled with the Botney Cut Formation overlain by up to 25 m soft, reddish-brown proglacial water-laid muds of the Sunderland Ground Formation (Cameron et al., 1992).

6.13 Twente Formation (periglacial deposits)

6.13.1 Dutch sector

Predominantly occurring in the eastern part of the Dutch sector (east of 4°E), extensive areas of periglacial sediments are present at or near the sea bed. The sediments consist

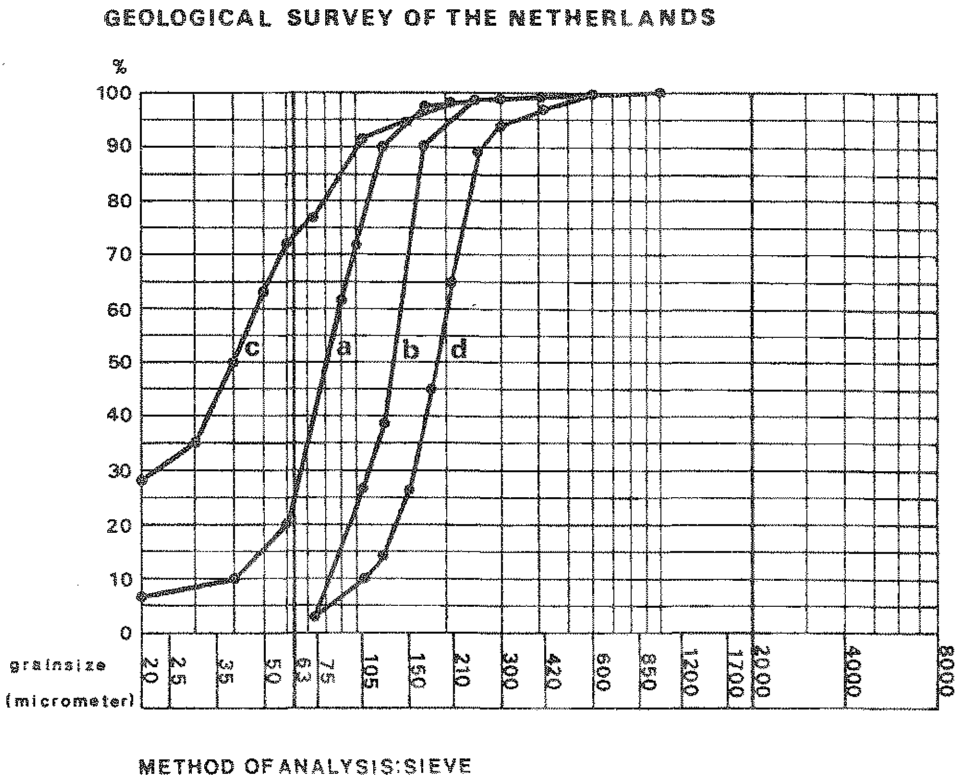


Fig. 85. Grain size analyses of the Twente Formation in boreholes F8-6 (a), F17-5 (b) and F14-6 (c).

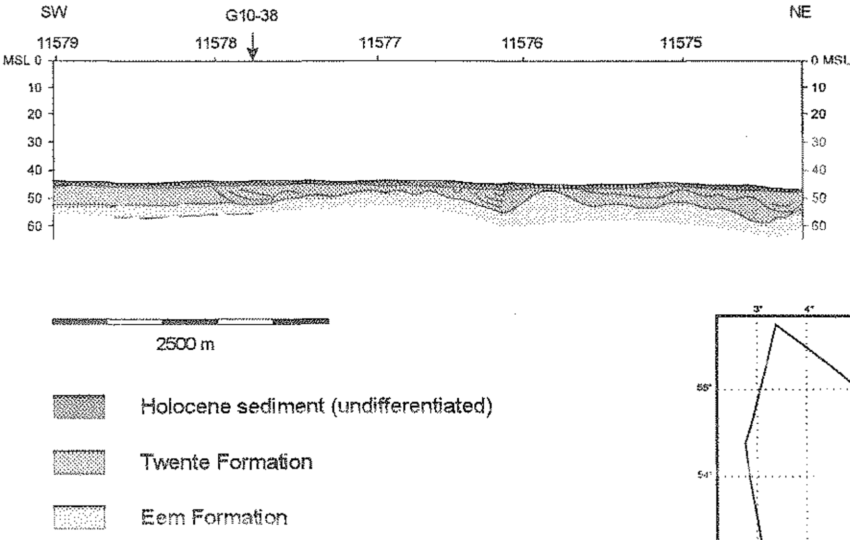
predominantly of very fine- to fine-grained, locally slightly silty to silty, laminated, locally slightly calcareous sands (Fig. 85) with organic matter. The thickness ranges between <1 m and about 12 m. Locally fine gravel (desert pavements) and mica are present. Lithologically the deposits are comparable to periglacial sediments found on land and described by Van der Hammen (1951). The deposits are referred to the Twente Formation, named after their type locality in the eastern Netherlands (Zagwijn, 1961). In several boreholes interstadial peat layers occur. The Twente Formation is often covered with an Early Holocene peat layer with soil horizons underlying the peat. Rooty material from the peat reaches into the underlying Twente Formation. The peat has been formed in marshes which covered the area during the Early Holocene.

The age of the Twente Formation ranges from Early to Late Weichselian (see Table 8).

In the Dutch sector the formation has been sampled in hundreds of boreholes and cores some of which are described below.
In the northern part of the Dutch sector, indications of a Weichselian age for the eastern extension of the formation, were given by De Jong (1974) based on pollen analyses of samples of borehole F5-5. In this borehole between 54 m and 53.75 m below MSL grey,

very fine-grained, slightly calcareous, micaceous sand was sampled containing some peaty layers and laminae. The spectra were poor in pollen, but more than 50% were derived from pre-Quaternary sediments thus indicating reworking of glacial deposits. The pollen of samples collected between 58.20 m and 57.90 m below MSL indicated deposition in an open landscape with subarctic conditions, such as occurred in the Early Weichselian (pollen zone EW Ia). De Jong concluded however that these conditions also prevailed during earlier stages of the Pleistocene. On the seismic profile, run over this borehole, the marine Eem Formation was interpreted as underlying the deposits. Therefore it may be concluded that the periglacial deposits are Early Weichselian in age and that the overlying fine sand deposits postdate the Early Weichselian. East of this borehole, core F6-10 sampled, between 46.60 m and 46.50 m below MSL, a layer rich in organic detritus with fine sand. Pollen analysis indicated that the deposits are derived from Scandinavian fluvioglacial sediments because of the high content of Tertiary pollen (Miocene) and seeds of *Alnus, Menyanthus, Potamogetes,* spores of *Azolla filiculoides*, and mosses, charcoal, lignite and amber (De Jong, 1972b). In borehole A17-3, to the north-west of borehole F5-5, the formation, sampled between 43.20 m and 41.70 m below MSL, consists of very fine- to fine-grained, non-calcareous sand with, at the top, a layer of 0.1 m clayey peat, and in turn overlain by 8.50 m of Holocene marine sand. Pollen analysis of the clayey peat recorded a high percentage of herbs (56%) indicating deposition in an open landscape, probably during the Late Dryas Stadial pollen zone LW III (De Jong, 1974). Further to the north-east borehole F3-2 also recorded, between 43.60 m and 42.50 m below MSL, very fine sand with a mossy peat layer. The sediments are underlain by marine sediments of the Eem Formation. South-west of borehole F3-2, borehole F7-2 recorded, between 56.90 m and 56.10 m below MSL, a soft, calcareous, sandy clay and grey, very fine, non-calcareous, micaceous sand. Pollen analysis indicated deposition during the Late Dryas Stadial. The sediments are overlain by Early Holocene peat and clay deposits (De Jong, 1974).
Near the western margin of the Dutch sector borehole E2-3 contained an interesting sequence. Underneath the Dogger Bank Formation (see Chapter 6.4) the Twente Formation, between 63.50 m and 57.50 m below MSL, was sampled and consisted of grey fine sand containing occasional organic layers. Pollen analysis recorded high percentages of herbs indicating cold climatic conditions during the Pleniglacial. The deposits overlie the Elsterian Swarte Bank Formation (see Chapter 4.7).
Borehole G10-38 was drilled in one of the 6 m deep channels (between 50 m and 44 m below MSL) which are present in the north-western part of block G10. The channels are partly incised into older deposits of the Twente Formation and the Eem Formation. The fluvioperiglacial sediments of the infill consist of fine- to medium-grained sand with fine gravel (flint, chalk, red, sandstone, probably Triassic, and quartzite) (Fig. 86). In borehole F14-4, between 52.60 m and 51.90 m below MSL, fine, non-calcareous sand with some gravel was sampled. Heavy mineral analysis recorded a high percentage of garnet (38%) a mineral which is often found in Weichselian periglacial deposits in The Netherlands (Zandstra, 1970).

In the western part of the Dutch sector in borehole K1-10, between 51.75 m and 47.45 m below MSL, grey, very fine- to fine-grained, silty, and locally clayey, calcareous sand, with, at the base, a thin peat layer was sampled; locally the deposit contains some shell fragments. The formation is overlain by the fluvioglacial Well Ground Formation and is underlain by the Eem Formation. Pollen analysis recorded a high percentage of herbs indicating deposition during the Pleniglacial, most probably one of the interstadials (De Jong, 1981b).



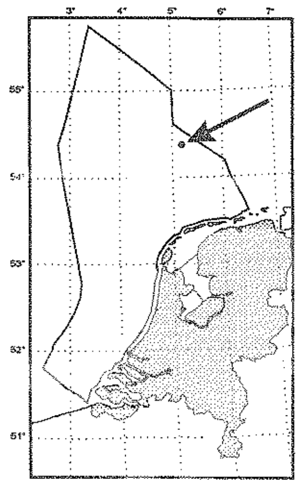
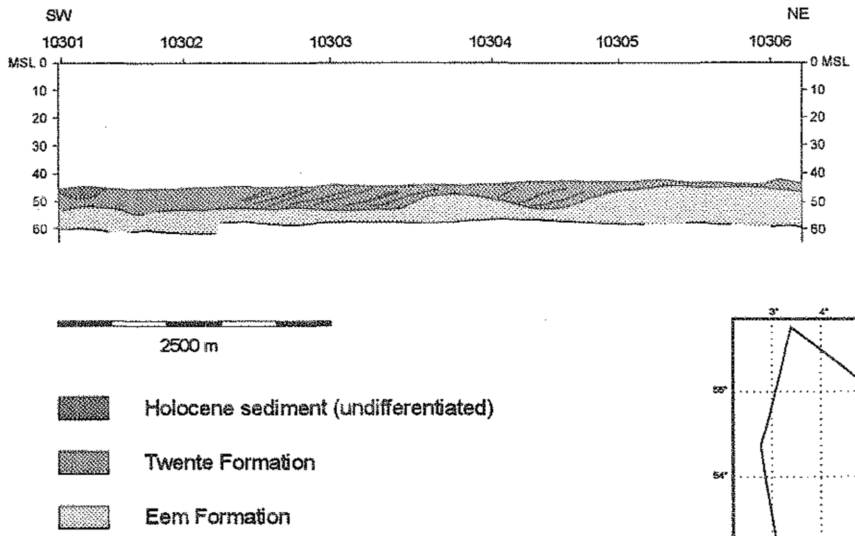


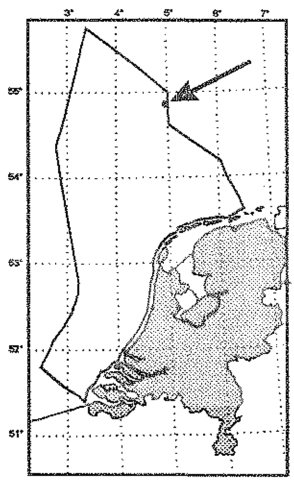
Fig. 86. Interpretation of a seismic profile over a Weichselian channel infilled with Twente Formation in block G10.

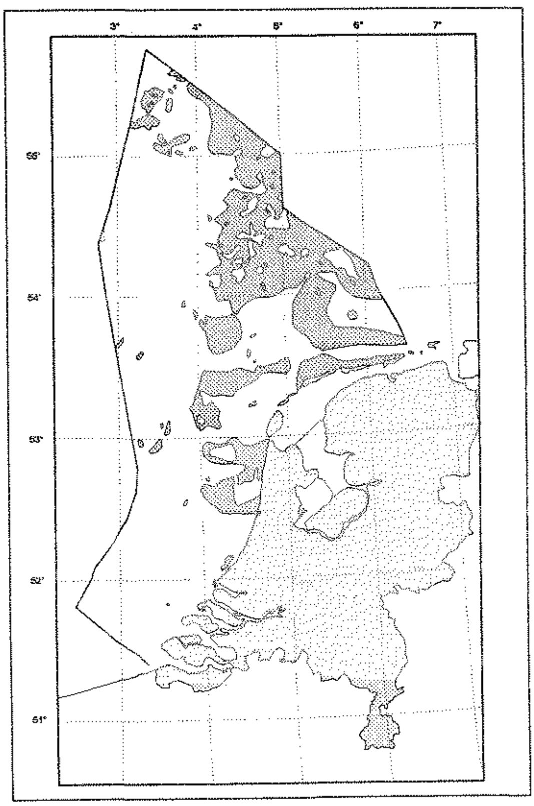
Near the coast of the isle of Texel in borehole L16-2, between 31.10 m and 29.98 m below MSL, the formation consists of grey, very fine, locally silty and clayey, laminated, slightly calcareous to calcareous sand overlain by 0.90 m of Holocene marine sediments. Pollen analyses recorded high percentages of herbs indicating deposition during a Pleniglacial phase of the Pleistocene (De Jong, 1972a). ^{14}C analysis of a humic clay layer in this borehole between 2.10 m and 1.90 m below sea bed indicate an age of 45,090 +3750/- 2550 BP (GrN-6766). This age places the deposits in the Middle Weichselian, Early Pleniglacial (Moershoofd Interstadial) (De Jong, 1973b; Zagwijn, 1989b). According to De Jong (1972a) the deposits overlie Eemian (pollen zone E6b) or Early Weichselian (pollen zone EW IV) on account of the high percentages of *Picea*.

In the southern part of the Dutch sector, near the coast of IJmuiden the formation has also been sampled in numerous boreholes. In one of the boreholes, Q11-483, the formation, sampled between 20.75 m and 19.85 m below MSL, consisted of olive-grey, very fine to medium-grained, non-calcareous sand. The sediments contained two layers of amorphous dark brown peat (at 20.57 m and 20 m respectively below MSL). Pollen analyses indicate an Allerød age for the lower peat layer and a Late Dryas age for the upper one (Cleveringa, pers. comm.). ^{14}C-datings indicate a Weichselian age of respectively 11,280 ±40 BP (GrN 16950) and 10,945 ±50 BP (GrN 16951).

One of the southernmost locations where the Twente Formation has been sampled lies west of the former island of Goeree. In core S6-1, between 24.70 m and 24.43 m below







Above:
Fig. 87. Interpretation of a seismic profile showing prograding reflectors in a Weichselian channel fill (Twente Formation) in block F6.

Left:
Fig. 88. The geometry of the Twente Formation in the Dutch sector of the North Sea.

MSL, at the base of a greyish fine sand, a peat layer was sampled which, according to the high content of herb pollen, was deposited during the Pleniglacial (De Jong, 1970). Diatoms and ostracods were absent as well as marine indicators like foraminifera (Du Saar, 1970c).

On seismic profiles the formation appears to vary considerably in thickness. In the north-western extension of the formation in the F and G blocks in channels, thicknesses reach up to 12 m

but range mainly between 2 and 6 m. The formation is predominantly homogeneous on seismic profiles, but locally shows subparallel reflectors. An infill with prograding reflectors has been observed in two channels in blocks F13 and F6 respectively (Fig. 87). In the remaining wide area of occurrence the formation is mainly observed as a sheet-like deposit (Fig. 88).

Most probably the formation originally had a much more westerly extent than at present. The fact that the formation is mainly present to the east of 4°E is most likely due to the prevailing westerly winds (Crommelin, 1964) transporting the material eastwards. The Brown Bank Formation in the central part of the southern Bight of the North Sea is only locally covered by periglacial deposits (Cameron et al., 1984b). Although this is probably partly caused by marine erosion during the Early Holocene transgression, it is not impossible that the periglacial sediments which covered the Brown Bank Formation were eroded and transported eastward during Weichselian Stadials. This view is supported by the fact that at the top of the Brown Bank Formation cracks are present which are filled with Holocene marine shelly sand indicating that the cracks were open at the start of the Holocene transgression. In the western part of the British sector north-west of the Brown Bank, between 52° 50'N/53° 10'N and 2°E/2° 40'E, the formation is only preserved in north-south oriented channels cut into the Brown Bank Formation (Cameron et al., 1984; Balson & Cameron, 1985).

North of the Frisian Islands the formation consists mainly of fluvioperiglacial sediments. In this area the aeolian sands have probably been transported by westward flowing streams into depressions.

The occurrence of the Twente Formation in the North Sea areas to east and west of the Dutch sector have been mapped in detail in the British sector, in the most north-western part of the German sector and in the most south-western part of the Danish sector. In the British sector the formation is only present in some north-south oriented channels (see above). In the German sector, the formation has been mapped in the most north-western part (Jeffery et al., 1991). Sindowski (1970) sampled Weichselian limnic and fluviatile periglacial deposits with thicknesses up to 17 m in boreholes in the German Bight. In borehole 7, between 33.25 m and 33 m below MSL, greyish-brown, fine, non-calcareous sand with organic matter was sampled while in borehole 15, between 55 m and 54 m below MSL, light-grey, non-calcareous, fine sand with humic layers was sampled. In borehole 17, between 36.25 m and 30.05 m below MSL, Sindowski sampled brown, fine, non-calcareous sand layered with organic matter. Pollen analyses indicated deposition during the Early Weichselian Brørup to post-Brørup interstadials. Several cores located just east of the Dutch sector also contained fine, non-calcareous sand of the Twente Formation suggesting that the deposits form a continuous sheet into the German sector.
In the Danish sector, except for the occurrence of periglacial sediments in the south-west part (Jeffery et al., 1990), there is no indication for the presence of Weichselian periglacial deposits.

In the southernmost part of the Dutch sector and in the Belgian sector only local erosional remnants of periglacial deposits have been recorded (Laban et al., 1992; Van Maenhout, 1992).

6.13.2 The Netherlands

The periglacial deposits sampled in the North Sea continue over large areas of The Netherlands where they form the so-called coversands and niveo-aeolian deposits (Edelman, 1951; Rutten, 1954; Zagwijn, 1961; Crommelin, 1964). These deposits, both on land and in the North Sea, form the western extension of an east-west running 'sand belt' of periglacial deposits from western into Central Europe (Cailleux, 1942; West et al., 1974; Catt, 1977; Ruegg, 1983; Koster, 1982, 1988; Vandenberghe, 1991).
In The Netherlands the Weichselian periglacial sediments are divided into the Older Coversand I and II which were deposited during the Pleniglacial and earliest Dryas Stadial respectively, and the Younger Coversand I and II deposited during the earlier Dryas Stadial and Late Dryas Stadial (Koster, 1988).

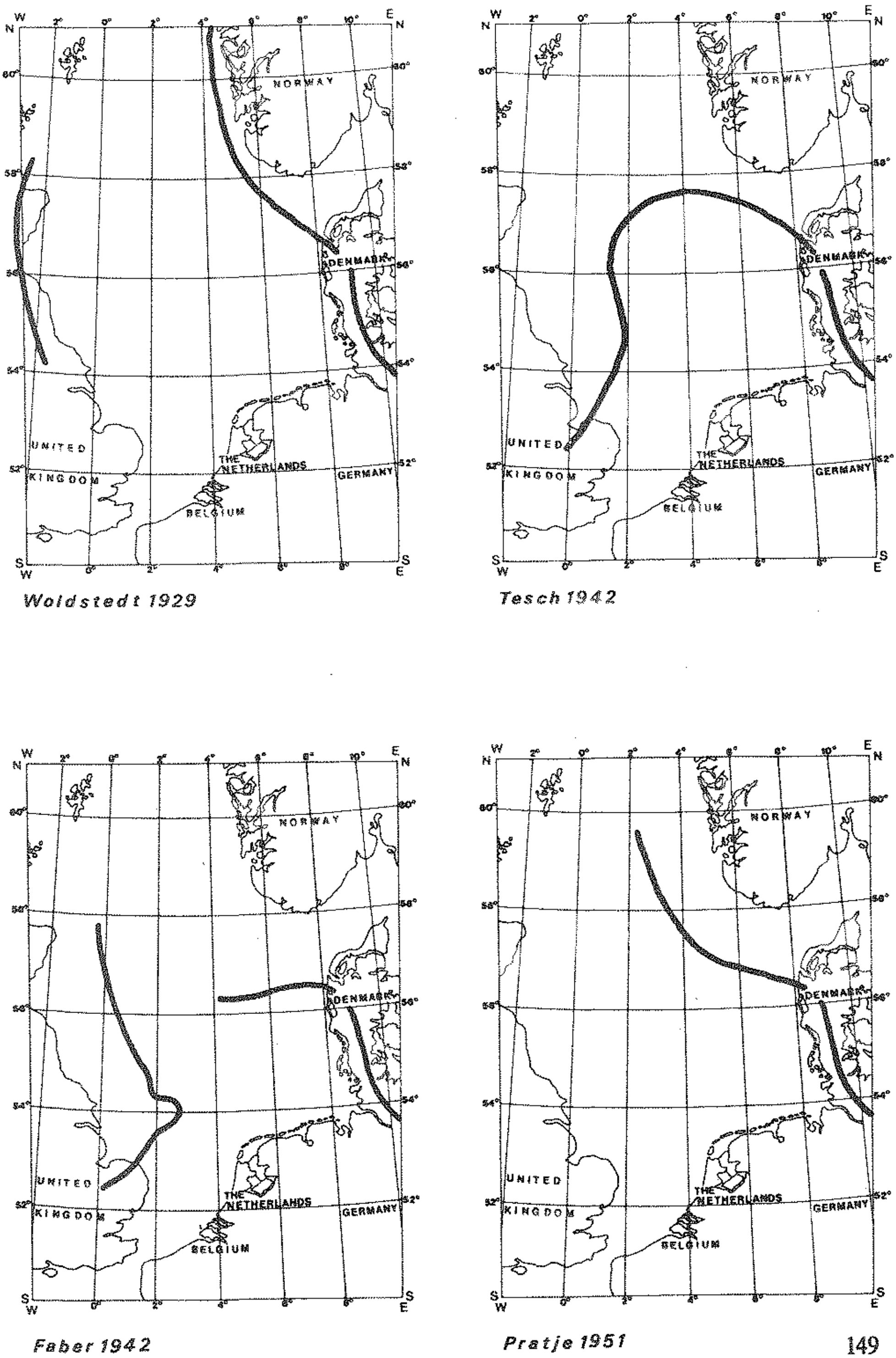
Mineralogical investigations by Crommelin (1964) showed that the Weichselian periglacial sediments in the northern Netherlands contain high percentages of garnet and also members of the tourmaline metamorphic group. The two components have lower values in the middle and southern part of The Netherlands. Crommelin (1964) concludes that there is a fair similarity between the coversand and the corresponding subsurface formation thus indicating a local origin of the sediments.

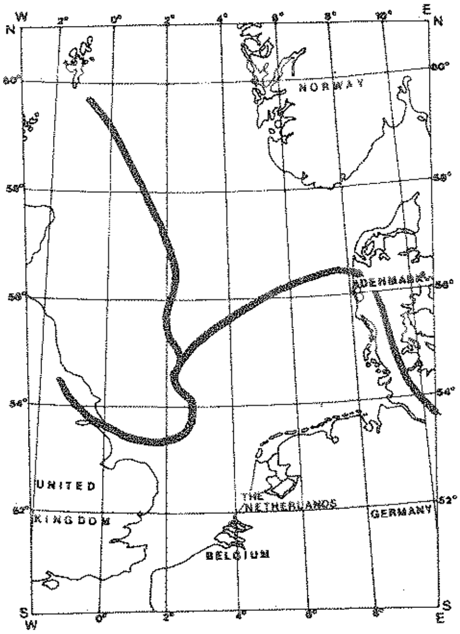
North of the Dutch coastal town of Schoorl the dune sands are non-calcareous, while to the south of the town the sands are predominantly calcareous. The non-calcareous sand has been derived from periglacial sand present in the North Sea whereas the calcareous sand is supposed to originate from the fluvial Pleistocene and younger coastal Holocene sediments to the south (Zagwijn, 1975a).

6.14 Maximum extent of the Weichselian ice sheet in the southern North Sea

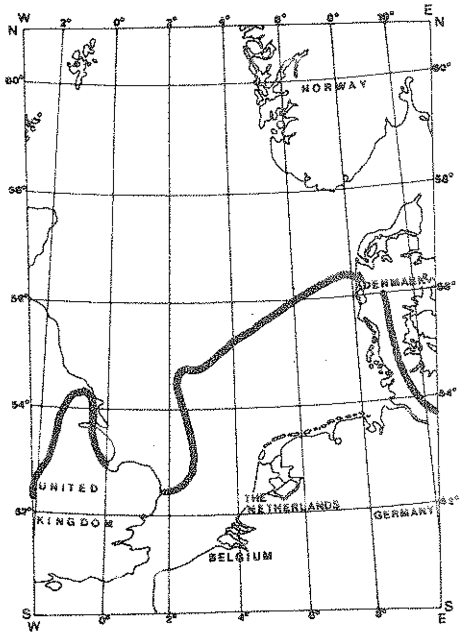
It is widely accepted that the maximum glaciation occurred around 18,000 BP (Jardine, 1979).
The maximum extent of the Weichselian ice sheets in the North Sea (Fig. 89) has been reconstructed by many authors predominantly by using evidence of the gravels exposed on the sea bed. All authors suggest a broadly similar location of the limits. Some assume a connection between the Scandinavian and British ice sheets, whereas according to others such a connection never existed. Woldstedt (1929, 1958) showed the line of the maximum extent of the Scandinavian Weichselian ice as running through Schleswig-Holstein and Jutland and crossing the present Danish coastline in northern Jutland, and thence extending north-west to the Norwegian coast. Tesch (1942) published a very similar maximum extent in Denmark with a line south-north through Schleswig-Holstein and Jutland and from northern Jutland into the North Sea, but then connecting the British with the Scandinavian ice sheet. Faber (1942) drew the same line through Jutland, but did not connect the British and Scandinavian sheets. Pratje (1951) presented a map showing three phases of Scandinavian land ice extending into the North Sea area, but suggested that the North Sea was not covered by British ice. Valentin, (1955) as stated earlier, connected the British and Scandinavian ice sheets. Flinn (1967) studied the enclosed deeps in the central northern North Sea and suggested that they marked an ice front at or soon after the last glacial maximum. Based on topographic features, Flinn drew flow lines of Scandinavian ice across the North Sea to the Orkney and Shetland islands. Scottish ice flowed out into the North Sea as far south as the southern limit of the Dogger Bank. Redding (1976) constructed a

Fig. 89. The ice limits of the Weichselian ice sheet in the North Sea after different authors.

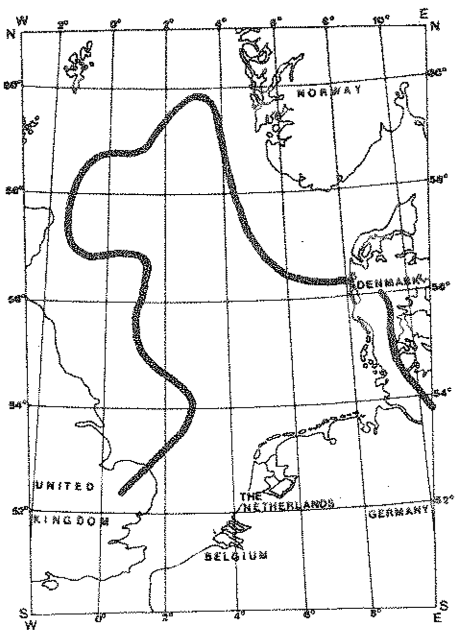




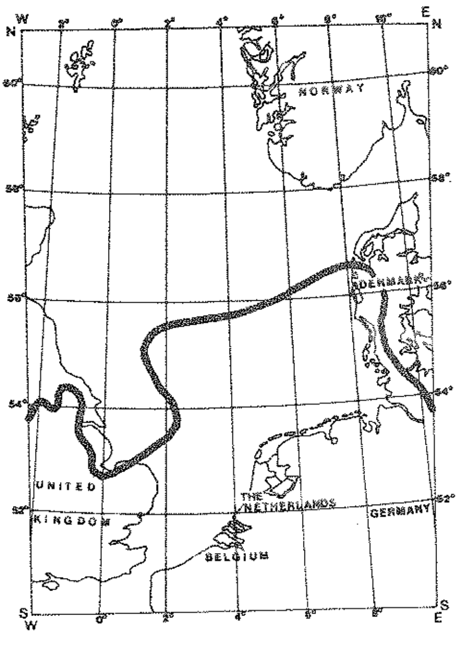
Valentine 1955



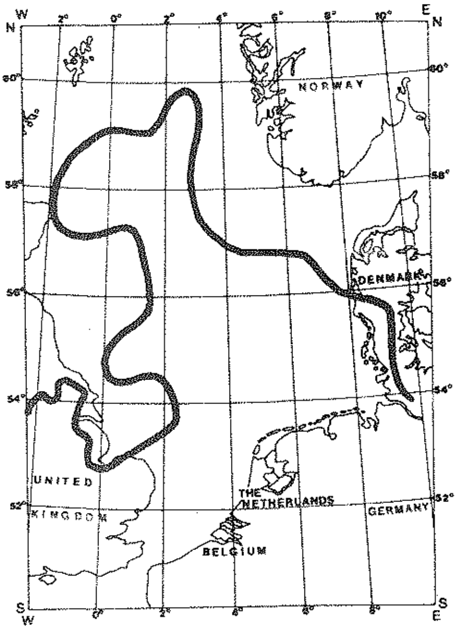
Redding 1976



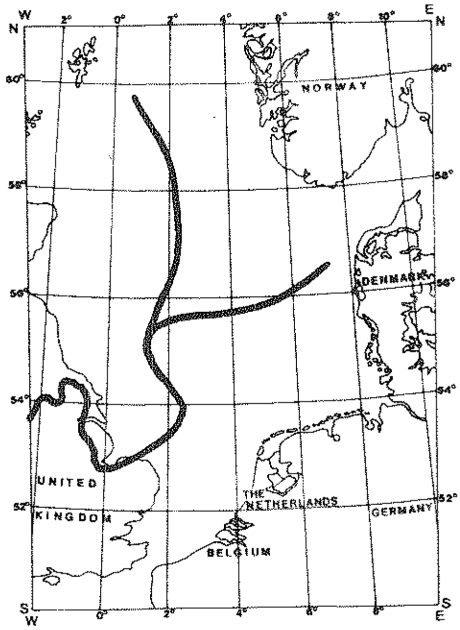
Overweel 1977



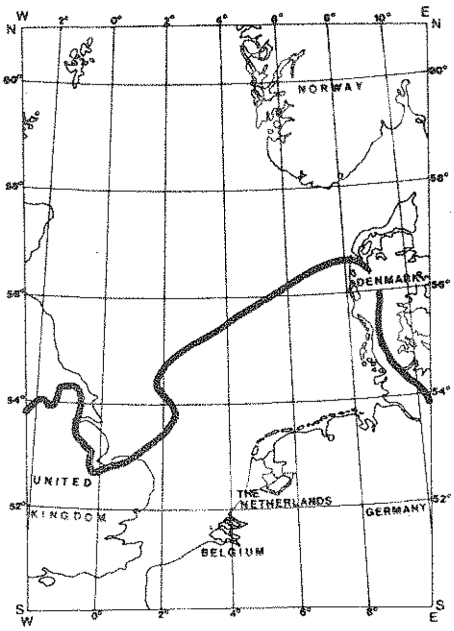
Boulton & Jones 1979



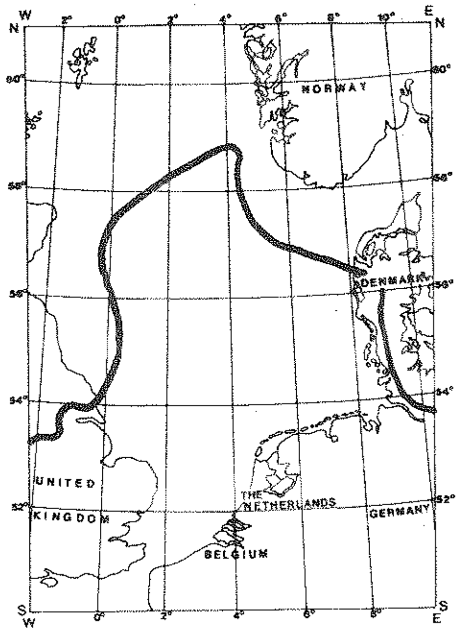
Jansen 1979



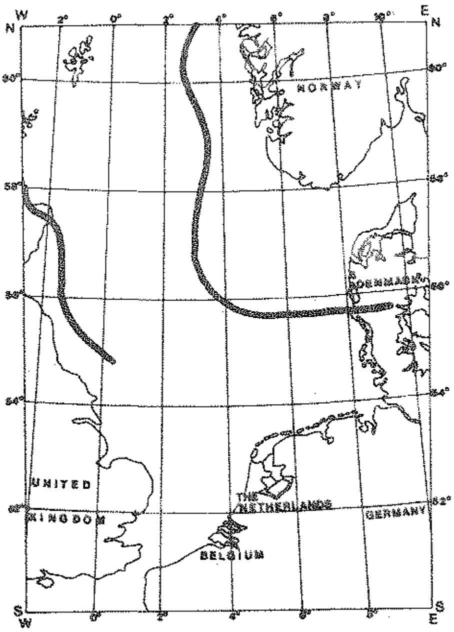
Andrews 1982
after Boulton et al. 1979



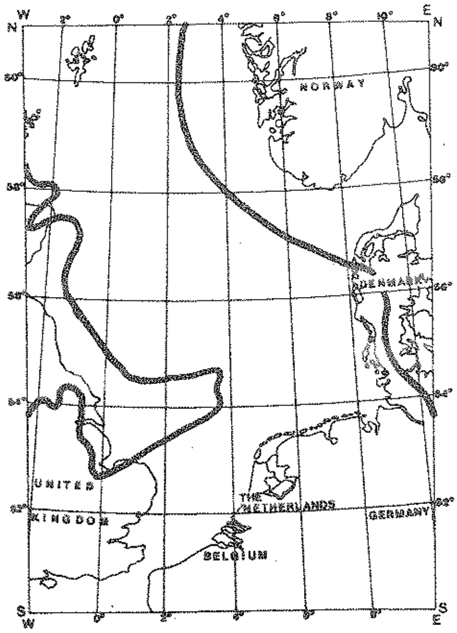
Andrews 1982
after Denton & Hughes 1981



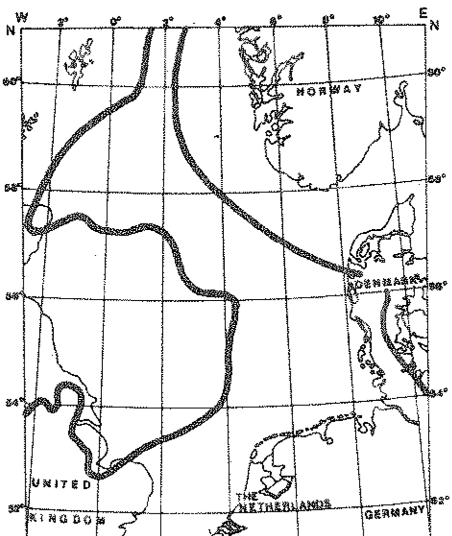
Boulton et al. 1985



Sutherland 1984 (western part)
Sejrup et al. 1987 (eastern part)



Long et al. 1988



Ehlers & Wingfield 1991

map showing the maximum extent of the Weichselian ice mass and like Valentin connected the British and Scandinavian ice sheets. Jansen, (1979) reconstructed a detailed ice limit in the British sector based on the occurrence of tunnel valleys and drainage channels and tentatively connected the British ice in the northern North Sea with the Scandinavian ice. Boulton & Jones, (1979) reconstructed the ice sheets in the western part of the North Sea and integrated the British and Scandinavian ice. Denton & Hughes (1981) also connected the British and Scandinavian ice sheets. Andrews (1982) used this map and constructed contour lines of the thickness of the ice. In the Dutch sector the thickness would have varied between nil and

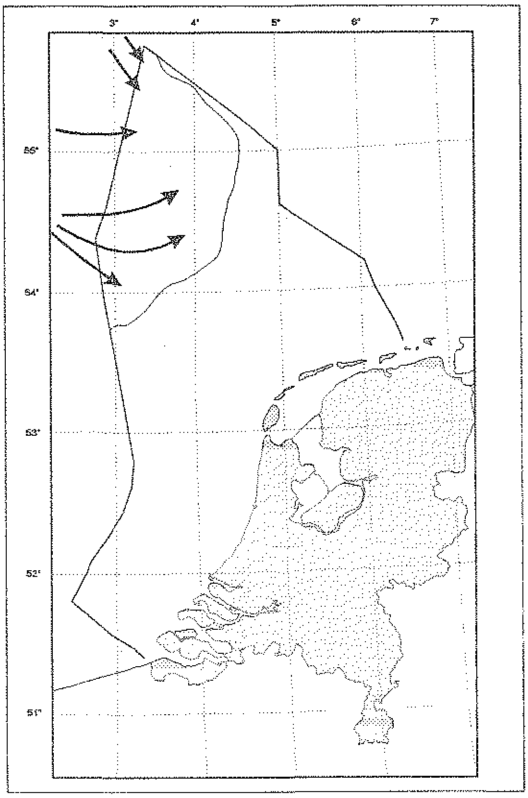


Fig. 90. The maximum extent of the British Late Weichselian ice sheet into the Dutch sector with probable flow directions. The arrows in the north indicate the youngest ice flow.

1000 m. Boulton et al. (1985) reconstructed the maximum extent of the Weichselian ice sheet using glacial features on the sea bed such as patterns of glacigenic longitudinal, and radial lineations. Sejrup et al. (1987) suggested an extension of the Scandinavian ice in the North Sea as far west as 0°E and quite separate from the British ice.

Recently Sejrup et al. (1994) published results of AMS radiocarbon datings on mollusc species like *Portlandia arctica* and *Yoldiella lenticula* and benthic foraminifera species like *Elphidium asklundi* and *Nonion orbiculare* from Weichselian marine deposits from a number of boreholes between northern Scotland and southern Norway. He concluded that the Scandinavian (Tampen Formation) and British (Dimlington Advance) ice sheets did not coalesce during the Weichselian glaciation. The Norwegian Trench off western Norway was deglaciated before 18,860 BP and after 15,145 BP (borehole 89.03), while in the centre of the northern North Sea marine sediments were dated 16,100 BP in age (borehole 77/2). As mentioned in the introduction of this Chapter it would appear an earlier advance of the British and Scandinavian Weichselian ice sheets did coalesce between 29,400 and 20,000 BP.

Ehlers & Wingfield (1991) constructed a map showing the maximum limit of the British ice sheet based on data obtained during the British/Dutch regional mapping programme (Fig. 89). A much extended north-east limit was shown than previously published. Question marks in the northern North Sea separated the assumed limits of the Scandinavian and British ice sheets. Wingfield (1989) showed a map in which the ice limits of the three last glaciations in the North Sea were based on glacial incisions. On the same map he showed the differences between these limits and the limits accepted by other authors both on land and at sea.

The revised map (Fig. 90) showing the extent of the British ice sheet into the Dutch sector is based on the occurrence of tills, deformation structures and subglacial valleys. Arrows indicate the suggested directions of the ice flows.

Observations of sea-level changes over the past 15,000 to 10,000 years in eastern Scotland have excluded models in which the British ice sheet extended over the North Sea and joined up with the Scandinavian ice sheet (Lambeck, 1991). Lambeck, (1991, 1993) drew ice limits based on glacial rebound calculations and did not connect the British and Scandinavian ice sheet during the Late Weichselian.

According to Lambeck (pers. comm.) the thickness of the Late Weichselian ice sheet in the E and F blocks of the Dutch sector has not been more than several hundreds of metres because no post-glacial rebound has been observed in that area.

The dating of the Late Weichselian ice sheet in Britain has been discussed in Chapter 5.15.

6.15 The Dogger Bank

During the recent British/Dutch regional mapping programme, seismic surveys and deeper boreholes have revealed new data about the sediments of the Dogger Bank and the underlying strata. The sediments of the upper few metres of the Dogger Bank are discussed in earlier publications (Borley, 1923; Baak, 1936 and Stride, 1959).

In several publications it has been assumed that the Dogger Bank already existed in its present form at the beginning of the Holocene transgression (Veenstra, 1969; Reinhard, 1974, Jelgersma, 1979) and that the bank was formed during the Pleistocene. The origin of the bank has been attributed to rivers, tidal eddies and to a scarp of Mesozoic rocks extending from the English coast (Stride, 1959). Veenstra (1969) suggested that the inner structure of the Dogger Bank consists of moraine ridges covered by solifluction, glacio-fluvial sediments and a thin layer of marine sediments. According to Reinhard (1974) the Dogger Bank was formed during the Saalian glaciation by the morphodynamically active confluence zone of the Oslo and Kattegat ice streams.
One of the first studies of gravel from the Dogger Bank was carried out by Tesch (1915) on material which was collected by fishermen from water depths of between 21 m and 38 m both on the bank itself and on its western slope. He distinguished twelve rock types. Nine types were of Scandinavian provenance notably black coloured flint, white-yellow chalk, Silurian limestone and dolomite, porphyries, orthoclase, basalt, diabase and amphibole schist and which had been transported during the Main Glaciation (Saalian). Three rock types were derived from the pre-glacial deltaic deposits of the rivers Rhine and Meuse and include quartz, quartzite and greywacke. Only two rock types were of British provenance notably basalt and Pliocene glauconitic sandstone nodules. The basalt was probably transported during the younger glaciation (Weichselian) and the sandstone during the Holocene transgression (Tesch, 1915).

Borley, (1923) described the sediments of the Dogger Bank and surrounding areas in great detail. He concluded that the major part of the bank was occupied by fine, singularly white sand with yellower sand and with very small quantities of medium sand and silt along the north-west slope and to the south-west. On the south-western part of the bank Borley sampled gravel of the fraction >15 mm in weight percentages of between 1 and 4.9%. In a smaller area on the central part of the bank he sampled gravel in the fractions between 1.5 mm and 14.9 mm and also in weight percentages between 1 and 4.9%. According to Borley the finer fractions were transported in an easterly direction by tidal currents.

Baak (1936) mineralogically examined 17 samples taken from the Dogger Bank as part of a regional study of the superficial sediments in the central and southern North Sea. Two main groups were distinguished, A and E, and also a transitional group between the two. The A-group is mainly of northern origin, probably from Scandinavia, and in which hornblende, epidote and garnet dominate. The E-group (English) is characterised by an association of garnet and augite with variable quantities of epidote and hornblende. On the map accompanying his thesis Baak showed that the south-western part of the Dogger Bank was occupied by the E-group and the transitional groups. Most of the central and northern part of the bank is covered by the A-group and this is also the case in the entire area between the Dogger Bank and the German Bight. By contrast the E-group is present in the area on the western and southern sides of the bank and between the Dogger Bank and the British coast.
Stride (1959) collected a series of ten sediment cores on the Dogger Bank. Most of the cores contained a shell layer grading up into fine sand. In the 3.80 m long core No. 2 a 1.14 m sequence of gravel and stones, sand and silt at the base is overlain by 1.21 m of sand fining upward. The upper 1.45 m consists largely of sand and silt laminae. According to Stride the uppermost sediments were deposited in an estuarine or tidal-flat environment. The gravel was composed of flint, chalk, andesite, some porphyrites, coarse red sandstone of Scottish Old Red Sandstone type, gneiss of (?) Norwegian type, lavas including rhomb-porphyries from the Oslo district, sandstone and coal. The provenance of the gravel was northern England, Scotland and Norway. Stride stated that the age of the Dogger Bank was Pleistocene because of the mammalian bones and also by the contained heavy mineral suites, as well as erratics, derived from England and Scandinavia. According to Stride the surface of the bank has probably not changed significantly since it was inundated by the post-glacial North Sea. Peat has been found at numerous locations on the top and sides of the bank which were all dated as Early post-glacial in age.
Oele (1969) stated that the peat sampled in shallow parts of the Dogger Bank must date from the Boreal or Early Atlantic.

During the regional mapping programme of the Dogger Bank area several boreholes up to 10 m in depth were drilled by RGD along the eastern slope of the bank. The sediments sampled consist of fine sand with intercalated gravelly layers. Borehole E1-4 was drilled to 6 m below sea bed on the East Bank which occurs on top of the Dogger Bank. Between 28.40 m and 23.40 m below MSL the sediment consists of fine gravel and marine shells. Petrological examination of 35 fragments of this gravel revealed flint, quartz breccia, white quartz, quartzite, granite, melaphyr, diabase and porphyries which, according to Zandstra (1972b), are of English and Scottish provenance and possibly also dark flint from Denmark (Jutland) and crystalline fragments from Scandinavia.
Borehole E1-10 was drilled on the eastern margin of the Dogger Bank with a water depth of 22.50 m. The sediments sampled consist of greyish, very fine- to fine-grained sand with shells and shell fragments and some scattered gravel including fragments of flint, quartzite, chalk, sandstone and quartz. At the base of the sandy unit, and between 36 m and 23.50 below MSL a silty clay with shell fragments was sampled overlying the glaciolacustrine clay of the Dogger Bank Formation. Pollen analysis indicated that the sandy sequence contains no pollen. Foraminiferal analysis indicated a low Boreal marine environment of deposition (Neele, 1991). The molluscs between 36 m and 31 m below MSL indicate a Holocene marine littoral environment of deposition, while between 31 m and 22.50 m a sub-littoral environment prevailed (Meijer, 1991).

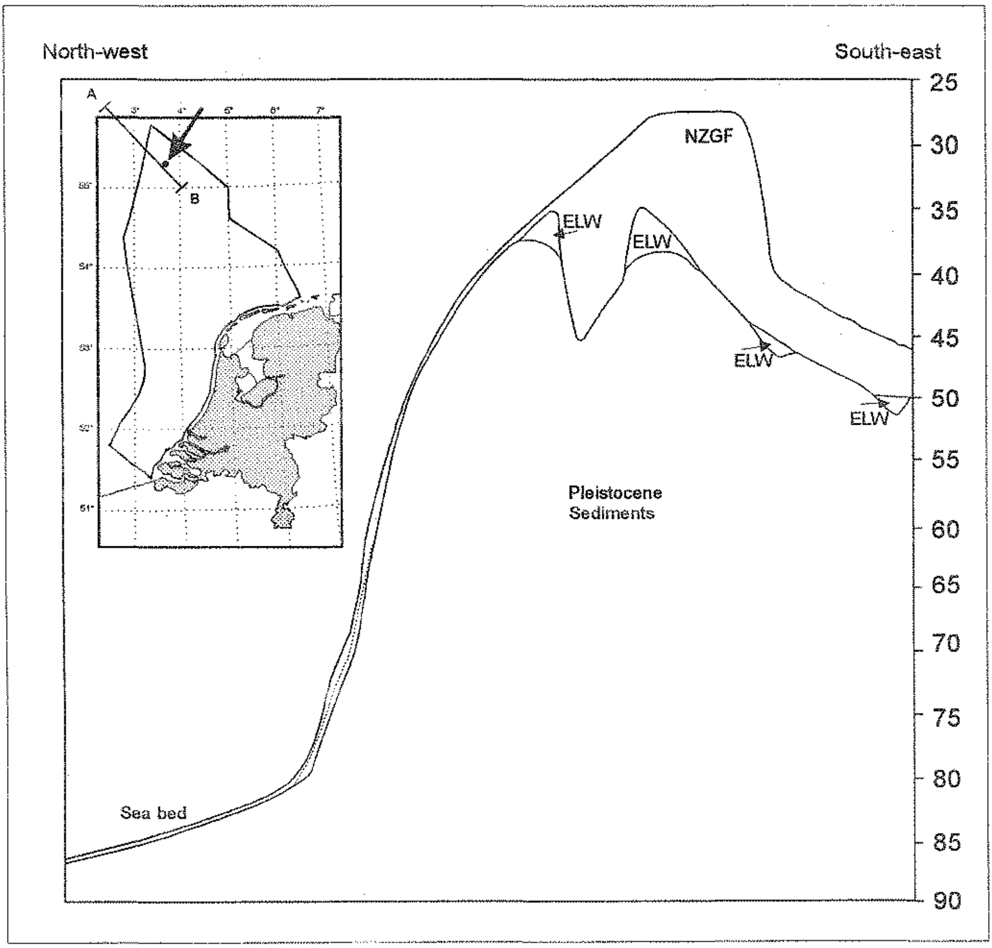


Fig. 91. Cross section over the Dogger Bank showing the Early Holocene Elbow Formation (ELW) underlying the Terschellingerbank Member of the Nieuw Zeeland Gronden Formation (NZGF). From seismic interpretations (after Jeffery et al., 1990).

Seismic surveys over the Dogger Bank contain profiles which indicate sand with, at the base of the bank on the eastern and towards the north-eastern flanks, laminated units in depressions. These are interpreted as tidal flat deposits (Jeffery et al., 1990) (Fig. 91).

6.16 Drainage during the Weichselian

During the Weichselian the rivers Rhine and Meuse flowed through the North Sea area in a more or less southern direction and building out their deltas towards the south-west (Laban et al., 1992). South of the present remains of this delta depressions occur which are partly filled with fluviatile sediments. Borehole BH 89/1 was drilled in one of the depressions in the Belgian sector. A ^{14}C-dating of a sample at ± 61 m below MSL recorded an age of 39,000 (+7000, -4000) BP (Maenhout, 1992). In the delta itself, in the fluviatile Kreftenheije Formation (Zonneveld, 1958), layers with pumice fragments have been found

(Laban et al., 1992) indicating deposition during the Weichselian when volcanoes were active in the German Eifel area (Meyer, 1986). Probably the layers with pumice fragments can be correlated with those found in the western Netherlands and which have been dated as deposited during the Allerød Interstadial (Verbraeck, 1974). Borehole S1-62 is an example of a sequence, containing layers with pumice fragments. In this borehole light grey coarse sand with gravel has been sampled, between 41 m and 38 m below MSL, and with a tuffaceous layer between 40 m and 39 m below MSL. The thickness of the Kreftenheije Formation ranges between <1 m and 20 m.

No evidence has been found for a cover to these fluviatile sediments on the Eemian to Early Weichselian Brown Bank Formation. The Early Holocene deposits overlying the Brown Bank Formation mainly consist of laminated fine silt with clay.

The drainage of the British ice sheet during the glacial maximum was most probably oriented towards the north-east following the main axis of the sub- and proglacial valleys. The meltwater had access to the North Sea because of the ice-free area between the British and Scandinavian ice sheets.

Evidence for drainage valleys of the Scandinavian ice sheet towards the west have not been found in the Dutch sector. The erosional base of the Weichselian channels in the eastern part of the Dutch G-blocks has a higher elevation than the Elbe valley which formed the main drainage valley in the German Bight (Figge, pers. comm.).

Besides bones of landmammals also bones of White Whales (*Delphinapterus leucas*) and of a Walrus (*Odobenus sp.*) were found on the sea bed in the southern North Sea between 52° 30' N and 53°00'N/2° 30'E and 3°00'E (Erdbrink et al., 1990; Van Bree & Post, 1994). ^{14}C datings of bone fragments of a White Whale and Walrus found near the Brown Bank revealed ages of respectively 34.600 -400/+500 BP and 50.000 -2000/+2800 BP indicating that these animals most probably occurred in the southern North Sea during the Middle Weichselian (Post, pers. comm.). It is known that White Whales swim upstream rivers over long distances. The occurrence of a Walrus, however, indicates a coastal zone environment. Sedimentary or seismic evidence for marine influence in this area during the Weichselian, however, has not been found yet. Contamination by weathering of the bones with ages of 50.000 years, causing a younger age, cannot be excluded (Van der Borg, pers. comm.).

6.17 Conclusions

The Brown Bank Formation was predominantly formed by marine and fluvial processes during the Late Eemian and Early Weichselian when the sea-level lowered and cold conditions prevailed. The formation probably remained partly free from cover by Weichselian sediments during glaciation as concluded from the abundant continental mammalian remains on top of and in the clay.

The firmness of the clay resulted most probably from dehydration by permafrost-related processes during Weichselian stadials.

Part of the formation in the northern S and T, and in the F and G blocks was deposited during the Late Weichselian by fluvial processes. These sediments are nevertheless regard-

ed as belonging to the Brown Bank Formation and show the same lithological characteristics.

The age of the Brown Bank Formation ranges from Late Eemian to Late Weichselian, Late Dryas Stadial or Early Holocene, Preboreal.

The fluvioglacial Well Ground Formation, which is largely made up of fine- to medium-grained sand, has been sampled in only a limited number of boreholes, not all of which penetrated the whole formation. It is difficult sometimes to distinguish the formation from underlying periglacial deposits which are locally present.

The stratigraphical position indicates the age of the Well Ground Formation is Late Weichselian.

A reconstruction of the extent of the Dogger Bank Formation over the entire area of the southern North Sea is not possible because of lack of data in both the Danish and German sectors. From the information available, however, it can be concluded that deposition of the glaciolacustrine clay in the Dutch sector was mainly British in origin. In the northeastern part of the Danish sector influence of Scandinavian ice was present because of the occurrence of glaciolacustrine sediments in the southern part of the Danish sector. The Scandinavian influence is also proved by the Tertiary pollen in glaciolacustrine clays in the south-eastern A-blocks.

During the deposition of the formation possibly at least three advances of British ice sheets took place. After the deposition of the lower part of the formation, and in which basal till has been observed, the ice margin shifted westward and deposition of glaciolacustrine sediments continued. During the second advance most of the formation was covered by ice during which time subglacial channels were formed and a basal till deposited (see Chapter 6.6). The presence of intercalating tills is also confirmed by the presence of microstructures visible in thin sections (Van der Meer & Laban, 1990).
A third advance took place from a northern direction (see Chapter 6.5).

The northern margin of the Dogger Bank Formation became probably ice-covered during the advance of the ice from the northwest by which the valleys filled with the Volans Member of the Dogger Bank Formation were cut into the glaciolacustrine clays present in the northern part of the Dutch and adjoining British sectors. These formations were more resistant against subglacial erosion than sand of the Yarmouth Roads Formation. As a result only the channels containing the Volans Member were incised in the Dogger Bank Formation during that advance.

The Dogger Bank Formation is mainly an ice-proximal glaciolacustrine deposit. The age of the Dogger Bank Formation is regarded as Late Weichselian on the basis of correlation with data from the Yorkshire coast.

The glaciomarine sediments of the Dogger Bank Formation found in the Dutch and Danish sectors can probably be correlated with the Late Weichselian marine deposits in northern Jutland. They represent a shallow marine facies with the shoreline not too far to the south (Fig. 74).

The depth of the glaciomarine sediments in the Dutch sector varies between 43 m and 48 m below MSL which is at a much higher level than the hypothetical coastline of about 64 m below present sea-level at 10,300 BP suggested by Jelgersma (1979). In addition, the isostatic movements caused by the ice load in the area and the subsequent glacial rebound as calculated by Lambeck (1995) does not agree with the position of the glaciomarine deposits. Another possibility is that deposition took place during the Early Holocene. However, this view is not supported by the fact that the foraminiferal content is not in accordance with the environmental conditions of deposition prevailing during the Early Holocene.

Sedimentary petrological and pollen analyses provide evidence that the tills in the western part of the Dutch sector consist of material of British origin. Deposition took place by an ice sheet advancing from the west-north-west. The thin sections and X-ray photographs show evidence that part of the till was deposited as a flow till overlying lodgement till. This indicates that during the advance of the ice, lodgement till was deposited during a phase of retreat of the ice and was subsequently overlain by flow tills. Deformation structures indicate glacial overriding after deposition.

The Bolders Bank Formation till can be correlated with the Basement, Skipsea and Drab tills of the Yorkshire coast; this suggests that the age of the formation is Late Weichselian.

The gravel deposits in and overlying the till are most probably of British provenance since no typical Scandinavian material or rock types from the continent have been recorded.

The gravel and blocks of the Indefatigable Grounds Formation near the Cleaver Bank were deposited during a stagnant phase of the Weichselian ice sheets which earlier had advanced from west- and north-westerly directions. The stagnation in the advance of the ice is deduced from the large amount of morainic material deposited on and around ice-pushed knobs. Elsewhere in the glaciated area morainic gravel is only locally present. The absence of ventifacts in gravel occurring on the present sea bed suggests deposition at the end of the glaciation, since no wind erosion took place after deposition. An alternative possibility is that the gravel was overlain by fluvioglacial sand deposits which were subsequently eroded during the Early Holocene transgression.

The sediments of the Indefatigable Grounds Formation were deposited during the Late Weichselian.

The ice pushed knobs are most probably formed by ice-push during the advance of the British ice sheet from the west north-west. Evidence for a standstill in the ice advance is shown by a cover of up to 2 metres of medium to coarse sand and gravel.
The other ice-pushed structures in the northern part, in the A-blocks, were most probably formed during ice advancing from a north-westerly direction.

The V-shape of the valleys, their irregular base and the fact that they have been eroded deeply into the Bolders Bank and Dogger Bank formations suggest that they have been formed subglacially. The radial pattern indicates the direction of ice movements. Most of the valleys are partly filled with Holocene marine sediments.

The fact that the Botney Cut is still partly open is probably due to tidal scouring. The tidal currents in this area have a west-east direction. The Botney Cut is a continuation of the Outer Silver Pit which is also an open valley. The same holds for the narrow open valley north of the Botney Cut.

A coarse basal infill with overlying draped sediments has only been recorded in the largest valleys in the south-western part of the Dutch sector. In the remaining, smaller, valleys the infill consists of more sandy sediments. The coarse-grained lower member of the infill was probably deposited when the subglacial valleys were still full of ice, while the muddy sediments were deposited as proglacial sediments after the retreat of the ice sheet.
Locally at the base of the Holocene peat has been sampled indicating that some of the valleys were still partly open at the end of the Weichselian.
The mixture of Early Holocene pollen with a high percentage of secondary pollen in the clay in the upper part of the Botney Cut Formation in borehole E11-4 indicates deposition during the Weichselian/Early Holocene. After deposition had come to an end, accumulation of peat began.

The age of the Botney Cut Formation is Late Weichselian.

From pollen analyses and ^{14}C-datings it is concluded that the periglacial sediments of the Twente Formation and intercalated peat horizons of the Twente Formation were deposited between the Early and Late Weichselian. It is not possible to further subdivide the periglacial deposits of the North Sea into Older and Younger Cover Sands as has been done on land, because the boreholes never include the complete sequence.

The sedimentary structures and lithology of the formation in the northern part of the Dutch sector indicate predominantly fluvioperiglacial deposition. The sediments in the northern area were locally derived from reworked and redeposited Saalian fluvioglacial sediments. The high percentage of garnet is similar to the percentages found in the Weichselian periglacial sands of the northern Netherlands.

Dogger Bank:
The underlying Weichselian Dogger Bank Formation dips eastward forming a core to the western part of the bank and against which the Dogger Bank has been built up. This therefore determines a maximum age for the bank.
The bank was probably formed initially by fluvioglacial sediments during the Weichselian glaciation. These sediments were partly reworked and redeposited during the Holocene transgression thereby burying the Early Holocene tidal sediments. Holocene reworking and redeposition of the sediments is indicated by their mollusc content.
Erosion by currents and waves together with washing of the finer fractions is probably responsible for the occurrence of gravel layers. In none of the recent boreholes have peat layers been encountered.
The investigations of Baak (1936) indicate that most of the superficial sediments on the central and east sides of the bank belong to the A-group. This group is predominantly present in the area east of the bank thus implying transport towards the bank from that area.
As far as the present author can ascertain the Pleistocene mammalian remains referred to by Stride (1959) have never been found on the Dogger Bank itself, but only in the area to the south.

Chapter 7

Comparison and discussion of the features and sediments of the three last glaciations

As described in Chapters 3 to 6, during the Middle and Upper Pleistocene ice masses invaded the southern North Sea at least three times and resulted in deformation and erosion of, and deposition on, the sea bed. In this Chapter the similarities and differences between the landforms and sediments produced by these glaciations in the Dutch sector of the North Sea will be discussed, as also features used to reconstruct the maximum limit of the ice sheets, the extent of Pleistocene glaciations in continental Europe, and the Holsteinian and Eemian marine transgressions. Examples of such landforms and sediments include the spectacular broad and deep valleys associated with the Elsterian glaciation compared to the relatively small and shallow subglacial valleys of the Saalian and Weichselian glaciations, and the almost complete absence of Elsterian tills compared to the extensive till plateaux of the Saalian and Weichselian (Fig. 92).

7.1 Glaciolacustrine, glaciomarine and fluvioglacial sediments

7.1.1 Elsterian

In the area south of the maximum ice limit no evidence has been found of glaciolacustrine and glaciomarine clays. Although these sediments should have been deposited during the advance of the ice up to its maximum extent they appear to be absent. The absence of the deposits in the non-glaciated area in front of the ice sheet probably indicates a short period of stagnant ice.
During the retreat of the ice, however, enormous amounts of muddy, fine-grained sediments were deposited. The upper infill of the subglacial valleys, together with depressions between the valleys, consist of thick layers of glaciolacustrine clays often overlain by glaciomarine clays. Ice-rafted debris (dropstones) in these sediments are rare.

Fine-grained fluvioglacial sediments have been sampled only in boreholes along the southern margin of the ice sheet. In the Dutch part of the Wadden Sea valleys filled with these sediments are preserved and are referred to the Peelo Formation. In the North Sea only thin layers of fluvioglacial sediments occurring within the clay of the Swarte Bank Formation have been proved to date.

7.1.2 Saalian

Stiff to very stiff glaciolacustrine clays were mainly deposited during the maximum of the Saalian ice sheet and largely occur in an extensive area north-west of the ice margin. The sediments form a sheet-like deposit and reach thicknesses of between 2 m and 8 m. The deposits thin in a north-westerly direction indicating deposition from the east and south-east. In the northernmost part of the Dutch sector however, an increased thickness also suggests that deposition may also have taken place from the north-east. There are no indications that the sediments were covered by ice after deposition. In four boreholes the deposits include ice-rafted debris (dropstones).

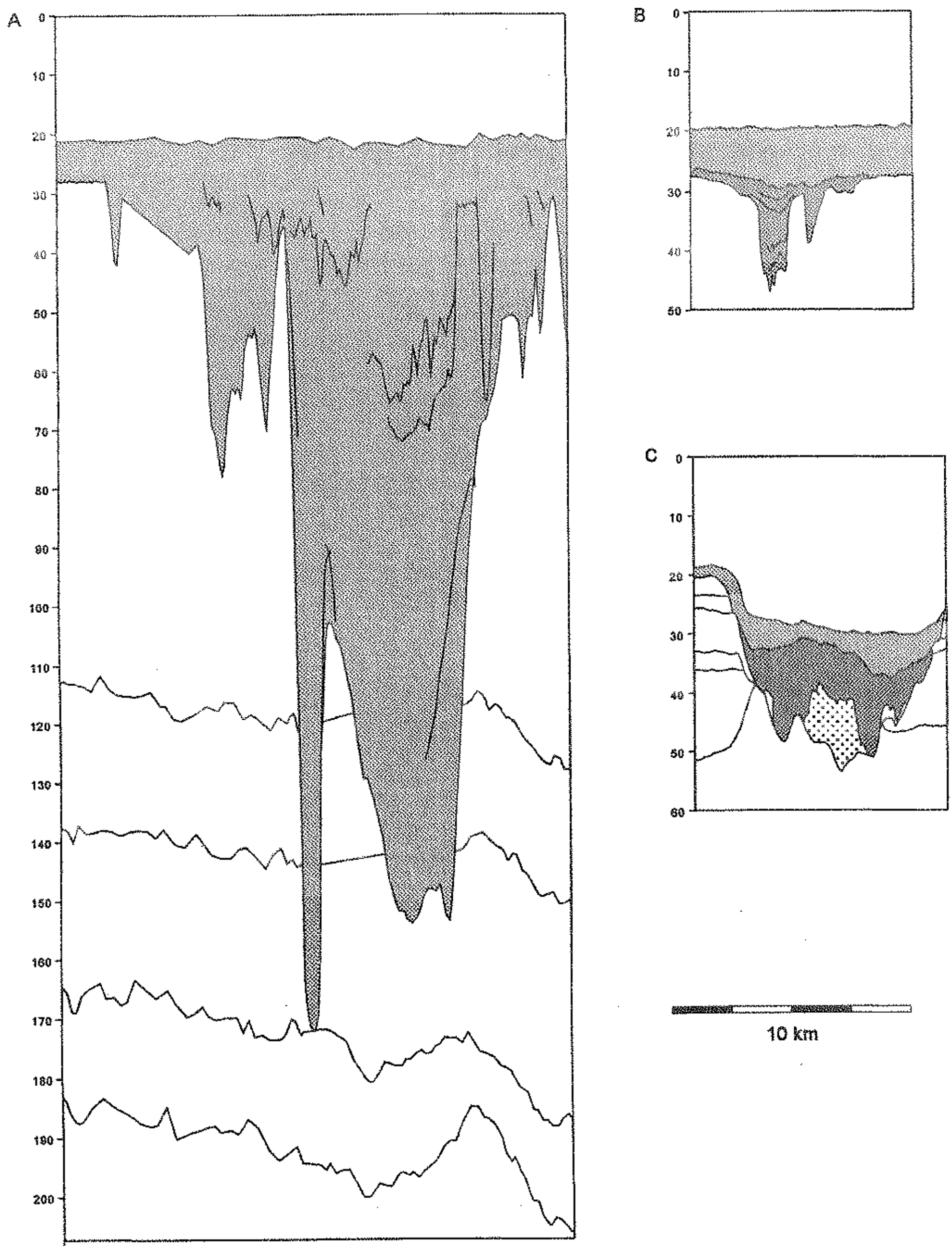


Fig. 92. Interpretations of seismic profiles over subglacial valleys A. Elsterian, B. Saalian and C. Weichselian.

Fluvioglacial sediments were deposited along the ice margin and overlie the glaciolacustrine clay. Because of marine reworking of the sediments, the deposits have only locally been preserved in-situ. The overlying marine Eemian sediments usually consist of medium-grained sand containing gravel of Scandinavian origin. Near the maximum limit of the ice gravel layers are present locally at the base of the Eemian marine sediments.

7.1.3 Weichselian

Stiff to very stiff glaciolacustrine clays are widespread in the north-west part of the Dutch sector and reach thicknesses of between 4 m and 10 m in the south-west and between 10 m and 20 m in the north-north-west. The clays probably extend much farther west into the British sector but they are seismostratigraphically indistinguishable from the overlying Bolders Bank Formation. In four boreholes ice-rafted debris has been encountered. Microstructures pointing to shearing, observed in these deposits, indicate that ice-loading took place during a later phase. Additional evidence is provided by the presence of patches of till, subglacial valleys and a tongue-shaped basin. In the northernmost part of the Dutch sector Late Weichselian glaciomarine clayey sediments are present.

Very fine- to fine-grained, fluvioglacial sediments both overlie and underlie the glaciolacustrine deposits and reach thicknesses of between 2 m and 4 m. The extent of the overlying fluvioglacial deposits however is much more local. The most extensive deposits are found in fan-like sheets which are present along the eastern and south-eastern margins of the ice.

7.1.4. Discussion

The sedimentary characteristics of the glaciolacustrine sediments of the last three glaciations are similar, and mainly consist of dense, stiff to very stiff clay with silty laminae and lenses.

The large amount of both Saalian and Weichselian glaciolacustrine clays deposited in front of the ice sheet may have been due to a longer period of stagnant ice during the maximum of the ice sheets than that which occurred during the maximum of the Elsterian ice. The thickness and geometry of the Saalian deposits is comparable to those associated with the Weichselian possibly indicating similar conditions. Another possibility is that the Saalian ice was stagnant for much longer time than the Weichselian sheet. The production of meltwater was probably higher during the Weichselian glaciation because of the presence of a dense braided pattern of subglacial valleys. Such features have yet to be proved in the Saalian glaciated area.

Foraminiferal evidence from boreholes indicate that the upper part of the Elsterian sediments were deposited in a glaciomarine environment. This is in contrast to the Saalian and Weichselian which are dominated by glaciolacustrine sediments. The infill of the upper part of the Elsterian subglacial valleys indicate that the sediments were deposited during the retreat of the Elsterian ice and probably not in front of the ice sheet during its maximum extent. This again contrasts with Saalian and Weichselian deposits which were laid down in front of their maximum ice extent. During the Elsterian ice retreat the crustal rebound was probably delayed (Lambeck, 1990) and a connection appears to have existed between the northern North Sea and the Dutch sector. In a depression in the northernmost part of the Dutch sector glaciomarine sediments were deposited during the Late Weichselian sea-level rise.

There are no indications that the Saalian glaciolacustrine deposits were overridden by the ice in contrast to Late Weichselian deposits.

Ice-rafted debris are rare in Elsterian glaciomarine sediments. The presence of ice-rafted debris in Saalian and Weichselian glaciolacustrine sediments however does not show that the debris were deposited by grounded icebergs.

7.2 Tills and glacial gravel

7.2.1 Elsterian

In the Dutch sector of the North Sea till has only been proved at one locality (borehole G16-22) where it is present on the floor of a glacial valley. The sedimentary character, microstructural fabric and the pollen content are similar to Saalian till sampled in the same borehole. The deposit is interpreted as a flow till. Elsterian tills have also been proved in a few locations in valleys in the northern Netherlands. Gravel deposited by the Elsterian ice has been proved at only two localities.

7.2.2 Saalian

Saalian till is widespread in the area north and north-west of the Frisian Islands where it forms a continuation of the till plateaux of the northern Netherlands. The tills can be divided into two groups. The tills in the western and northern part of the area are mainly greenish-grey to brown-greenish-grey, very sandy and contain less gravel than the tills sampled in eastern part of the till plateau in the Ems estuary. In the western area the till is underlain by Saalian periglacial sand which probably has been mixed contemporaneously during the deposition of the till. Microstructural characteristics indicate deposition as flow till. Gravel patches overlying the till or close to the till occurrence are of Scandinavian provenance. Along the western margin of the ice sheet in the North Sea no tills have yet been observed.

7.2.3 Weichselian

Between the British coast and the maximum extent of the Weichselian ice sheet in the Dutch sector, an almost continuous sheet of till is present. In the Weichselian tills near the Cleaver Bank, flow till overlying lodgement till can be distinguished based on evidence from their microstructural fabric. The till is locally overlain by gravel patches of British provenance. Lodgement till is also found interbedded in the glaciolacustrine clay indicating an earlier phase of advance of the ice.

7.2.4 Discussion

The tills of the three last glaciations in the Dutch sector of the North Sea are much thinner than those found in The Netherlands and Britain. Elsterian till is rare in the North Sea, but thin sections indicate that the genesis of the only Elsterian till sampled is similar that of the overlying Saalian till.
Visually the Saalian till sampled north of the Dutch coast is similar to the Weichselian tills sampled near the Cleaver Bank; both contain chalk pebbles and have been interpreted as

lodgement tills. Thin sections, however, have indicated that flow tills are also present. In The Netherlands most Saalian till is regarded as lodgement till.

7.3 Deformation structures

Deformation of the substrate by ice has been recorded in all the areas covered by the three glaciations. The Elsterian and Saalian ice sheets formed large tongue-shaped basins with icepush structures along their margins. No such large basins appear to be associated with the Weichselian glaciation in the Dutch sector of the North Sea. At only one location has a small shallow tongue-shaped basin with marginal deformation structures been recorded. Near the Cleaver Bank a number of broadly north-south trending ice-push knobs are present.

Ice-pushed ridges with dimensions similar to those in The Netherlands and Germany have not been recorded in the North Sea.

7.4 Subglacial valleys

7.4.1. Elsterian

A dense pattern of braided, wide, deep, (up to >400 m below MSL), eroded valleys are present in an east-west, relatively narrow zone within the glaciated area. A great number of these valleys indicate the enormous amount of meltwater which was released by the ice sheet and the high hydrostatic pressures which must have been generated. Three phases of infill can be detected in these valleys. The first phase largely consists of sand, while the second phase is dominated by glaciolacustrine clays. The third phase of infill took place in a mainly glaciomarine environment, and probably occurred during the retreat of the ice sheet. The occurrence of glaciomarine clays in depressions between the valleys also indicates the presence of a marine environment during the third phase. The upper part of the infill of the valleys locally consists of Holsteinian marine sediments.

7.4.2 Saalian

Narrow, isolated valleys extending down to approximately 90 m below MSL, and probably of subglacial origin, have been recognised on seismic profiles mainly along the margin of the maximum extent of the ice sheet. The infill consists, at the base, of Saalian glacial and fluvioglacial sediments overlain by Eemian marine sediments which form the bulk of the sequence.

7.4.3 Weichselian

Four types of Weichselian subglacial valleys have been recorded in the British and Dutch sectors of the North Sea. The first type consists of a braided system of mainly narrow, deep valleys up to 80 m below MSL, along the eastern limit of the ice sheet. The valleys were formed by ice advancing from a westerly direction. The infill at the base consists partly of coarse-grained, fluvioglacial sediments, overlain by fine-grained muddy proglacial lake deposits. The upper part of the infill consists of marine Holocene sediments.

The second type of valley is present in the northern part of the Dutch sector and the adjoining part of the British sector. These valleys, up to 80 m below MSL, are incised into Saalian and Weichselian glaciolacustrine formations. The incision took place during a later

phase of the glaciation by ice advancing from the north-west. The valleys are completely filled with glaciolacustrine clay. The third and fourth type of valley are not recorded in the Dutch sector and are discussed in Chapter 6.

7.4.4 Discussion

Comparison of subglacial channels and processes of infill during the three glaciations reveals that the valleys were formed near the margin of the maximum extent of the ice sheets. The upper part of the Elsterian valleys are almost completely filled with proglacial sediments while the Saalian valleys are largely filled with marine Eemian Interglacial with glacial and proglacial deposits forming only a minor proportion of the total. The first type of Weichselian valley is, like the Saalian valley, only partly filled with glacial, glaciolacustrine and fluvioglacial sediments and for the main part consists of Holocene marine sediments. This probably indicates that these valleys were filled with ice at the end of the respective glaciations. The second type of Weichselian valley, occurring in the northernmost part of the Dutch sector, is completely filled with glaciolacustrine sediments. The first type of valley probably dates from the final phase of the glaciation whereas the second type was probably formed during an earlier phase due to the fact that they are completely filled with glaciolacustrine clay. The ice sheet must still have been active to produce such large quantities of meltwater deposits.

7.5 Extent of the ice sheets in Europe

7.5.1 Pre-Elsterian glaciations

Little is known about the glaciations of the oldest Early Pleistocene cold stages and phases: the Praetiglian Stage (Zagwijn, 1975b) and succeeding Tiglian C4c cold phase, the Eburonian Stage, the Menapian Stage and the Middle Pleistocene cold phases of the Cromerian Stage. Important Quaternary sequences are present in Poland. The oldest stage of which indications are found for cold conditions is the Fernandow Interglacial. At Fernandow in eastern Poland a characteristic pollen sequence is present showing two climatic optima with intervening cold intervals. Lake sediments deposited during cold conditions underlie the sediments of the lower optimum and overlie the upper one. The whole sequence is underlain and overlain by tills (Janczyk-Kopikowa, 1975; Mojski, 1985). The Fernandow Interglacial correlates probably with the Cromerian in western Europe (Zagwijn, 1993). In the Kleszczow Graben in Central Poland, however, no Lower Pleistocene and Cromerian deposits have been found (Krzyszkowski, 1994a, 1994b).
In the valley of the River Dnepr in White Russia an ice lobe extended south of Kiev in the Ukraine while another lobe in the River Don valley reached as far as the Don bend in Russia. Farther eastwards, the ice limit extended beyond the River Volga near the great Volga bend and towards and into western Siberia (Krasnenkov et al., 1987). This glaciation is probably of Early Cromerian age (isotope stage 16) (Zagwijn, 1993).

In the North Sea region there is insufficient data to draw any conclusions regarding the maximum extent of any pre-Elsterian ice sheet.

7.5.2 Elsterian and younger glaciations

At the maximum of the Elsterian glaciation the Scandinavian ice extended across the North Sea as far as the north-west coast of The Netherlands and the Ipswich area of East Anglia in Great Britain. In continental Europe the ice margin extended from the northern Netherlands in a south-easterly direction to the Dresden area in Germany. Farther east it continued along the Sudetes and Carpathians into the Ukraine and southern Russia and then in a more or less easterly direction into Siberia (Rühle & Mojski, 1968; Rozycki, 1972; Mojski, 1985, 1993). In the Kleszczow Graben, near Belchatow, in Central Poland, the Elsterian glaciation is represented by three tills which are separated by cold periods, but without any signs of reforestation (Krzyszkowski, 1994).

In Western Europe the Saalian ice extended farther than the Elsterian ice. The ice limit extended from the central Netherlands in a south-east direction towards Duisburg in Germany and, from thence eastwards more or less following the line of the Elsterian limit into southern Poland and Russia (Mojski, 1985, 1993).
Saalian ice of British origin possibly extended into the northern North Sea; glaciomarine sediments have been interpreted as such in the Central North Sea (Stoker & Bent, 1985; Stoker et al., 1985a, b) and were recorded in a borehole near Devil's Hole (Knudsen & Sejrup, 1993).

The Weichselian Scandinavian ice sheet extended into northern Poland, Russia and Germany (Mojski, 1985, 1993). The ice limit did not reach as far as the southern North Sea, but ran from northern Jutland north-westward into the northern North Sea. The Scandinavian ice sheet in the North Sea reached thicknesses of 1500 m along the Norwegian coast, while the British ice in the North Sea attained thicknesses of up to 500 m (Boulton et al., 1985). Weichselian British ice extended into the North Sea as far south as the Wash in northern East Anglia the ice margin then running in a north-easterly direction towards 4°E and 55°N. From this position in the North Sea the ice margin swung to the north-west and thence back towards the British coast. In the model produced by Boulton et al. (1985) the Scandinavian and British ice sheets did not coalesce. In the model by Denton & Hughes (1981) however, both ice sheets became joined and reached thicknesses of between 1000 m and 2000 m in the central North Sea. The widely differing results of modelling by authors indicates that the reconstruction of former ice sheets requires much more work and data processing regarding the behaviour and processes at work in major ice sheets.

7.6 Interglacial sediments in the North Sea

7.6.1 Holsteinian

Sediments of the Holsteinian Interglacial are present over almost the entire Dutch sector of the North Sea except for the southern part of the southern Bight (Zagwijn, 1979). It is difficult to distinguish Holsteinian sediments from Eemian and Holocene. The Holsteinian deposits are mainly poor in molluscs no typical association having been established (Gibbard et al., 1991; Meijer, pers. comm.). Grahle (1936) cited the species *Tridonta montagui* as characteristic of the marine Holsteinian but according to Meijer (pers. comm.) this species is also present in younger marine sediments of the North Sea. In addition a typical foraminiferal association has not been established for the North Sea (Van Leeuwen, pers. comm.). Analytically the pollen spectra resemble that of parts of the Eemian. The me-

gaspores of *Azolla filiculoides* however is an indicator which has no significance after the Holsteinian.
The sediments locally form the infill of depressions in Elsterian valleys and exhibit continuous deposition indicative of gradual passage from arctic marine to boreal marine conditions. The southern limit of Holsteinian sediments is more or less coincident with the maximum extent of the Elsterian ice. The Holsteinian transgression started directly after the end of the Elsterian glaciation. The sediments are predominantly made up of fine sand and silty sand with clay and are mainly poor in shells and shell fragments. The sediments locally contain some fine gravel. Correlation of the Holsteinian Egmond Ground Formation is possible on seismic profiles because of a distinct reflector present at the top of the formation.

7.6.2 Eemian

The Eemian Interglacial sediments are, like the Holsteinian, also present over almost the entire Dutch sector, but thin or even disappear below the Weichselian Dogger Bank Formation in the north-west of the area. In the southern part of the area, the thickness decreases in a westerly direction from the Dutch coast and is absent in the southern part of the British sector (Cameron et al., 1984b). The occurrence of Eemian sediments is probably limited to depressions left behind by the Saalian ice and deposition of marine sediments most likely took place before the glacio-isostatic rebound. The Eemian sediments within and around the margin and maximum extent of the Saalian ice sheet are predominantly medium-grained and contain Scandinavian gravel. The sediments are usually rich in molluscs. Two different mollusc associations can be recognised in the Dutch sector of the North Sea. In the coastal area a mainly 'warm' lusitanic association is present with indicator species such as *Divaricella divaricata, Bittium reticulatum* and *Venerupis aurea senescens* (Spaink, 1958). The fauna entered the North Sea through the Strait of Dover which was open during the Eemian Interglacial. In the southern and central part of the Dutch sector another association is present which is more or less similar to that of the present North Sea fauna. This is indicative of two main climatic periods; one in which milder climatic conditions than at present were prevailing and one in which broadly similar conditions to those of today obtained.
Foraminifera present include distinctive species like *Elphidium translucens* van *Elphidium lideoense* (Van Leeuwen, pers comm.). The Early Eemian pollen assemblages are similar to those of the Early Holocene. The Middle and Late Eemian contains pollen assemblages in which Carpinus dominates thus differentiating it from the Holocene. Six pollen zones can be distinguished. The oldest Eemian pollen zone recognised so far in the North Sea is E2a (De Jong, 1991). The presence of diatom species like *Edictya oceanica, Rhabdonema adriaticum, Cocconeis scutellum, Stephanopyxis turris* and *Melosira sulcata* indicate Eemian marine conditions (Du Saar, 1971; De Wolf, 1991).

7.7 Conclusions

The Early Pleistocene and Elsterian ice margins reached much farther south in eastern Europe than in western Europe. However, the Saalian ice margin in western Germany and The Netherlands, reached further south than the Elsterian ice sheet. The margins of the Weichselian ice sheets reached considerably less farther south both in western and eastern Europe than either the Elsterian or the Saalian. In the southern North Sea the Elsterian ice sheet extended far to the south from the northern Netherlands to southern England.

The Saalian Scandinavian ice sheet did not cross the North Sea however, and was limited to its eastern side. During the Weichselian the Scandinavian ice sheet only entered the North Sea west of Norway in the north-east, while the British ice extended far to the east into the Dutch sector.

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Table 1 Location and water depth of boreholes discussed in Chapter 3

Borehole number	Geographical co-ordinates	Water depth below MSL
F8-6	54° 34' 10"N/04° 28' 02"E	49.50 m
G16-22	54° 00' 06"N/05° 00' 02"E	40.00 m
A-1	55° 24' 20"N/05° 24' 21"E	44.00 m
A-2	55° 24' 21"N/05° 03' 34"E	44.00 m
L10-6	53° 24' 17"N/04° 12' 11"E	30.35 m
8903	60° 38' 24"N/03° 43' 24"E	320.00 m
DR 88/30	64° 20' 48"N/07° 48' 18"E	242.00 m
79/08	53° 20' 20"N/02° 25' 44"E	21.50 m
E1-10	54° 59' 28"N/03° 03' 25"E	22.50 m
E8-6	54° 32' 44"N/03° 24' 16"E	40.50 m
74/10	56° 10' 30"N/00° 51' 42"W	72.00 m
74/12	56° 10' 30"N/00° 53' 12"W	72.00 m
81/26	58° 08' 21"N/00° 10' 38"W	122.00 m

Boreholes in The Netherlands

Borehole number	Amersfoort co-ordinates	Heigth/depth Datum (NAP)
5B-7	X 156.880/Y 594.400	-18.00 m
6D-49	X 197.525/Y 582.000	-0.40 m
9B-36	X 114.805/Y562.970	+2.00 m
12D93	X 234.480/Y 560.190	+11.90 m
10B/191	X 159.275/Y 567.210	+0.50 m
14E-110	X 126.375/Y546.335	-0.50 m

Table 2 Location and water depth of boreholes discussed in Chapter 4

Borehole number	Geographical co-ordinates	Water depth below MSL
9B 36	53° 03' 12"N/ 04° 47' 17"E	+2.00 m
14 E 110	52° 54' 16"N/ 04° 57' 54"E	00.50 m
A5-9	55° 41' 43"N/03° 29' 38"E	46.30 m
E1-10	54° 59' 28"N/03° 03' 25"E	22.50 m
E2-3	54° 53' 44"N/03° 31' 15"E	41.50 m
E8-4	54° 32' 44"N/03° 24' 16"E	40.50 m
F2-6	54° 54' 41"N/04° 38' 12"E	41.70 m
F3-2	54° 59' 30"N/03° 54' 29"E	41.50 m
F3-45	54° 51' 15"N/04° 43' 40"E	42.60 m
F8-6	54° 34' 05"N/04° 28' 01"E	49.50 m
F15-30	54° 12' 58"N/04° 49' 43"E	48.00 m
K7-7	53° 37' 07"N/03° 05' 58"E	38.60 m
K12-29	53° 27' 33"N/03° 54' 21"E	28.00 m
K13-5	53° 15' 56"N/03° 06' 57"E	26.80 m
K13-6	53° 16' 55"N/03° 12' 45"E	27.55 m
K13-7	53° 17' 37"N/03° 12' 31"E	27.50 m
K13-8	53° 18' 35"N/03° 12' 45"E	25.90 m
K15-9	53° 16' 36"N/03° 52' 24"E	27.85 m
L1-4	53° 56' 34"N/04° 08' 31"E	41.95 m
L2-19	53° 57' 30"N/04° 29' 30"E	45.30 m
L4-21	53° 43' 31"N/04° 05' 55"E	40.00 m
L7-10	53° 32' 17"N/04° 12' 12"E	28.05 m
L7-11	53° 32' 18"N/04° 12' 09"E	27.75 m
L11- 7	53° 23' 29"N/04° 20' 16"E	28.00 m
L11-71	53° 20' 11"N/04° 22' 39"E	30.00 m
L14-66	53° 18' 28"N/04° 27' 07"E	29.00 m
M11-39	53° 27' 35"N/05° 32' 56"E	02.00 m
P3-25	52° 54' 54"N/03° 50' 12"E	26.00 m
P4-9	52° 42' 45"N/03° 19' 28"E	31.80 m
P5-4	52° 45' 00"N/03° 25' 00"E	33.80 m
P5-15	52° 42' 23"N/03° 20' 39"E	42.60 m
P5-19	52° 42' 03"N/03° 21' 31"E	43.40 m
P7-7	52° 32' 24"N/03° 15' 48"E	34.20 m
P8-7	52° 36' 58"N/03° 20' 06"E	40.00 m
Q1-24	52° 55' 17"N/04° 05' 54"E	26.00 m
P4-8	52° 42' 37"N/ 03° 19' 50"E	38.20 m
Q5-209	52° 44' 50"N/ 04° 32'13"E	20.00 m

Table 3
Location and depth of ice-push structures on seismic records (Sonia) along the Brown Bank (after Bammes, 1986).

Plot and Serial No.	Water depth in m	Depth to top of formation (m)	Direction of ice pressure	Co- ordinates
5452 1	38.50	42.50	E (?)	52° 46'49"N 03° 21'44"E
6635 2	40.50	44.50	(?)	52° 46'16"N 03° 21'20"E
6632 3	42.00	44.50	W(?)	52° 44'56"N 03° 20'21"E
6616 4	41.50	44.50	W	52° 43'51"N 03° 20'36"E
5500 5	40.00	42.50	W	52° 43'30"N 03° 19'57"E
6610 6	40.00	45.00	E	52° 42'50"N 03° 19'52"E
5508 7	41.50	43.50	W	52° 42'17"N 03° 19'46"E
6597 8	43.50	46.00	(?)	52° 41'47"N 03° 20'44"E
5531 9	42.00	42.00	W	52° 41'17"N 03° 20'46"E
6592 10	19.50	?	?	52° 40'13"N 03° 20'44"E
6573 11	40.00	40.00	W	52° 38'34"N 03° 21'53"E
6556 12	42.00	43.00	E	52° 37'35"N 03° 21'46"E
5596 13	38.50	38.50	W	52° 37'03"N 03° 21'00"E
6550 14	37.50	40.50	W	52° 36'34"N 03° 21'10"E
5606 15	39.00	44.00	E	52° 36'01"N 03° 20'46"E
6534 16	42.00	46.50	W	52° 35'25"N 03° 20'23"E
5632 17	35.50	35.50	W	52° 34'56"N 03° 20'13"E
5716 18	34.00	37.00	W	52° 29'30"N 03° 20'49"E
6462 19	33.00	41.00	E	52° 27'47"N 03° 19'23"E
5773 20	30.50	36.50	E	52° 26'14"N 03° 21'10"E
5813 21	28.00	39.5	E	52° 24'09"N 03° 21'23"E
6411 22	33.00	38.50	W	52° 22'25"N 03° 20'33"E

Table 4 Co-ordinates and water depth of boreholes discussed in Chapter 5.

Borehole number	Geographical co-ordinates	Water depth below MSL
Dutch sector		
A5-9	55°41'43"N/ 03°29'38"E	46.30 m
A9-9	55°32'51"N/03°44'55"E	35.20 m
A12-2	55°24'00"N/03°48'00"E	33.00 m
B13-5	55°15'50"N/04°04'40"E	45.20 m
E1-10	54°59'28"N/03°03'25"E	22.50 m
E8-4	54°32'44"N/03°24'16"E	40.50 m
F3-2	54°59'30"N/03°54'24"E	41.50 m
F3-5	54°40'48"N/04°33'12"E	48.00 m
F4-3	54°41'48"N/04°05'30"E	46.00 m
F12-2	54°10'30"N/04°32'25"E	47.10 m
F16-5	54°04'43"N/04°11'36"E	47.60 m
F17-5	54°05'39"N/04°31'03"E	48.00 m
F17-9	54°08'54"N/04°31'07"E	48.00 m
G11-1	54°22'20"N/05°28'04"E	43.00 m
G16-22	54°00'06"N/ 05°00'02"E	40.00 m
G18-2	54°08'18"N/05°53'14"E	43.50 m
K1-10	53°54'27"N/03°16'15"E	39.45 m
K4-3	53°47'07"N/03°01'22"E	42.00 m
K15-4	53°13'27"N/ 03°53'47"E	27.00 m
K16-27	53°18'29"N/03°56'49"E	25.90 m
K17-2	53°05'01"N/03°31'32"E	30.00 m
K17-4	53°13'27"N/03°53'47"E	27.15 m
K18-11	53°07'33"N/03°54'52"E	25.40 m
K18-16	53°02'55"N/03°59'43"E	28.30 m
K18-21	53°03'11"N/03°59'32"E	28.20 m
K18-23	53°02'45"N/03°59'00"E	27.80 m
K18-24	53°57'14"N/04°30'47"E	41.00 m
L2-19	53°57'41"N/ 04°29'48"E	45.30 m
L4-21	53°43'31"N/04°05'56"E	40.00 m
L7-11	53°32'18"N/04°12'04"E	27.75 m
L10-2	53°29'17"N/04°11'30"E	26.40 m
L10-6	53°24'17"N/04°12'11"E	30.00 m
L10-96	53°22'15"N/04°15'36"E	28.20 m
L11-7	53°23'29"N/ 04°20'16"E	75.90 m
L11-8	53°23'46"N/04°22'09"E	26.80 m
L11-71	53°20'11"N/04°22'39"E	30.00 m
L15-46	53°16'31"N/ 04°56'04"E	09.75 m
L15-56	53°16'21"N/04°43'29"E	22.50 m
L15-65	53°13'15"N/04°40'06"E	23.30 m
L17-2	53°09'07"N/04°25'00"E	29.00 m
L17-151	53°05'53"N/04°39'29"E	20.20 m
L18-59	53°09'56"N/04°44'52"E	13.50 m
L18-60	53°09'19"N/04°43'05"E	15.00 m

Borehole number	Geographical co-ordinates	Water depth below MSL
Dutch sector		
L18-74	53°08'02"N/04°41'16"E	17.20 m
L18-83	53°05'13"N/04°41'25"E	13.20 m
L18-95	52°59'56"N/04°41'07"E	03.60 m
M4-4	53°47'33"N/05°14'58"E	33.60 m
M5-7	53°42'31"N/05°34'55"E	27.90 m
M7-46	53°39'42"N/05°10'23"E	29.69 m
M9-11	53°34'49"N/05°59'38"E	29.40 m
M11-39	53°27'35"N/05°32'56"E	02.00 m
M13-8	53°18'20"N/ 05°10'30"E	18.20 m
N9-10	53°30'14"N/ 06°41'23"E	13.00 m
N9-11	53°30'05"N/ 06°40'48"E	13.53 m
N9-12	53°30'02"N/ 06°40'57"E	14.38 m
N9-15	53°30'06"N/ 06°41'15"E	17.32 m
N9-20	53°30'01"N/ 06°40'32"E	12.20 m
N9-24	53°31'12"N/ 06°48'08"E	13.30 m
N9-25	53°31'23"N/ 06°48'04"E	15.70 m
N9-26	53°31'08"N/ 06°48'41"E	14.30 m
N9-32	53°31'07"N/ 06°49'11"E	15.00 m
N9-33	53°31'06"N/ 06°48'51"E	14.70 m
N9-35	53°51'05"N/ 06°48'10"E	13.30 m
N9-36	53°31'23"N/06°46'24"E	15.40 m
N12-1	53°28'37"N/06°50'01"E	13.62 m
N12-3	53°29'35"N/ 06°40'28"E	20.40 m
N12-11	53°29'45"N/ 06°40'44"E	12.50 m
N12-12	53°29'53"N/ 06°40'31"E	12.30 m
N12-14	53°29'58"N/ 06°40'40"E	11.56 m
N12-15	53°29'55"N/ 06°40'49"E	12.60 m
N12-19	53°29'49"N/ 06°40'16"E	12.40 m
N12-23	53°29'56"N/ 06°41'13"E	12.50 m
N12-30	53°28'28"N/ 06°50'03"E	12.30 m
P3-24	52°57'05"N/03°55'19"E	27.00 m
P3-26	52°52'34"N/03°54'52"E	27.40 m
P3-27	52°55'01"N/03°57'59"E	26.30 m
P3-28	52°55'07"N/03°59'56"E	25.90 m
P3-40 (CPT)	52°55'38"N/03°58'05"E	26.45 m
P3-51	52°57'00"N/03°59'54"E	28.30 m
P3-94	52°57'00"N/03°59'54"E	28.30 m
P5-4	52°45'00"N/03°25'00"E	33.80 m
P15-36	52°17'27"N/03°56'11"E	25.00 m
Q1-93	52°58'21"N/ 04°06'29"E	28.00 m
Q3-51	52°57'20"N/04°40'12"E	02.90 m
Q4-44	52°49'02"N/04°14'11"E	25.70 m
Q4-49	52°44'57"N/04°10'03"E	26.50 m
Q5-24	52°40'20"N/04°34'01"E	17.00 m

Boreholes in The Netherlands

Borehole number	Amersfoort co-ordinates	Heigth/depth Datum (NAP)
9B-36	X 114.805/Y562.970	+2.00 m
9D-181	X 111.090/Y 551.860	+0.25 m

Borehole number	Geographical co-ordinates	Water depth below MSL
Danish sector		
BH89/7A	55° 56' 48"N 04° 20' 42"E	48.00 m
Roar 41	55° 27' 48"N 04° 40' 00"E	47.10 m
Skjold 21	55° 32' 06"N/04° 55' 00"E	39.50 m
Dan 31	54° 29' 56"N/05° 09' 00"E	42.80 m
Nordsø A-1	55° 24' 20"N/05° 24' 21"E	44.00 m
Nordsø A-2	55° 24' 21"N/05° 03' 34"E	44.00 m
British sector		
78/08	53° 20' 20"N/02° 25' 44"E	21.50 m
79/8	53° 20' 20"N/ 02° 25' 47"E	21.50 m
81/26	58° 08' 24"N/00° 10' 37"W	122.00 m
J14-1	53° 19' 19"N/02° 34' 30"E	29.48 m

Table 5 Co-ordinates and water depth of boreholes discussed in Chapter 6

Borehole number	Geographical co-ordinates	Water depth below MSL
Dutch sector		
22b	52° 36' 06"N/03° 07' 18"E	36.00 m
A8-2	55° 36' 19"N/03° 23' 28"E	41.50 m
A8-5	55° 34' 37"N/03° 24' 06"E	40.35 m
A8-25	55° 37' 51"N/03° 25' 00"E	43.10 m
A12-2	55° 24' 00"N/03° 48' 00"E	30.48 m
A17-3	55° 07' 05"N/03° 33' 50"E	33.20 m
A18-3	55° 05' 48"N/03° 52' 31"E	45.00 m
A18-16	55° 05' 48"N/03° 52' 31"E	46.40 m
D18-32	54° 00' 21"N/02° 57' 34"E	43.20 m
D18-33	54° 03' 24"N/02° 57' 40"E	44.30 m
E1-4	54° 55' 42"N/03° 05' 32"E	23.40 m
E1-10	54° 59' 28"N/ 03° 03' 25"E	22.50 m
E2-1	54° 59' 30"N/03° 32' 30"E	38.00 m
E2-3	54° 53' 44"N/03° 31' 15"E	41.50 m
E3-5	54° 57' 25"N/ 03° 55' 09"E	47.10 m
E4-1	54° 40' 26"N/03° 18' 13"E	40.00 m
E4-10	54° 42' 32"N/03° 14' 58"E	42.00 m
E4-24	54° 44' 30"N/03° 13' 17"E	40.50 m
E5-2	54° 45' 30"N/03° 31' 13"E	44.10 m
E6-1	54° 44' 57"N/03° 50' 12"E	47.60 m
E7-5	54° 31' 33"N/03° 15' 10"E	39.00 m
E8-3	54° 30' 13"N/03° 32' 30"E	44.00 m
E8-4	54° 32' 44"N/ 03° 24' 16"E	40.50 m
E8-13	54° 37' 34"N/03° 25' 05"E	41.70 m
E11-4	54° 29' 24"N/03° 29' 24"E	43.20 m
E16-3	54° 03' 04"N/03° 12' 08"E	39.20 m
E16-39	54° 01' 39"N/03° 11' 45"E	37.00 m
E16-542	54° 09' 15"N/03° 12' 51"E	38.20 m
E16-551	54° 09' 16"N/03° 13' 59"E	38.80 m
E16-557	54° 08' 44"N/03° 13' 01"E	37.60 m
E18-4	54° 02' 29"N/ 03° 45' 51"E	46.40 m
F3-2	54° 59' 30"N/04° 59' 24" E	41.50 m
F3-4	54° 59' 05"N/04° 49' 57" E	41.10 m
F4-3	54° 41' 48"N/ 04° 05' 30"E	46.00 m
F4-5	54° 49' 12"N/ 04° 07' 13"E	47.00 m
F5-5	54° 40' 48"N/04° 33' 12"E	48.00 m
F6-10	54° 41' 54"N/04° 46' 08"E	45.80 m
F7-2	54° 34' 52"N/04° 10' 17"E	48.10 m
F8-6	54° 34' 05"N/ 04° 28' 01"E	49.50 m
F13-3	54° 15' 12"N/04° 09' 06"E	49.30 m
F14-4	54° 10' 30"N/04° 32' 25"E	47.10 m
F14-13	54° 10' 22"N/04° 39' 13"E	46.00 m
Dutch sector		
F14-6	54° 12' 07"N/ 04° 32' 10"E	48.00 m
F17-5	54° 05' 39"N/ 04° 31' 03"E	48.00 m
G10-38	54° 27' 30"N/05° 15' 00"E	42.40 m
G17-19	54° 07' 29"N/05° 35' 04"E	39.30 m
G18-25	54° 02' 29"N/05° 45' 01"E	37.40 m
J3-29	53° 57' 56"N/02° 51' 17"E	40.00 m
K1-10	53° 54' 27"N/ 03° 16' 15"E	39.45 m
K1-13	53° 57' 31"N/03° 06' 01"E	36.20 m
K1-106	53° 58' 55"N/03° 02' 33"E	40.00 m
K1-108	53° 54' 39"N/03° 10' 43"E	43.10 m
K15-4	54° 13' 27"N/ 03° 53' 47"E	27.00 m
K18-16	53° 01' 14"N/ 03° 53' 13"E	25.00 m
K18-21	53° 03' 11"N/ 03° 59' 32"E	28.20 m
L16-1	53° 06' 18"N/03° 10' 14"E	30.20 m
L16-2	53° 08' 12"N/04° 06' 41" E	27.50 m
P5-4	52° 45' 00"N/03° 25' 00"E	33.80 m
P7-8	52° 39' 14"N/03° 16' 31"E	39.00 m
Q11-483	52° 28' 35"N/04° 27' 43"E	19.50 m
S1-62	51° 59' 47"N/03° 16' 29"E	34.00 m
S6-1	51° 50' 00"N/03° 40' 00"E	23.20 m
British sector		
146 (Veenstra)	53° 52' 30"N/02° 23' 18"E	45.00 m
2 (Stride)	54° 46' 30"N/02° 02' 00"E	29.26 m
77/2	58° 29' 30"N/00° 30' 18"E	147.00 m
Norwegian sector		
89.03	60° 38' 18"N/03° 43' 24"E	300.00 m
Danish sector		
Roar 41	55° 46' 30"N/04° 40' 00"E	47.10 m
Dan 31	54° 29' 56"N/05° 09' 00"E	42.80 m
Skjold 21	55° 32' 06"N/04° 55' 00"E	39.50 m
BH6	55° 30' 56"N/06° 10' 05"E	40.50 m
BH 89-7A	55° 56' 48"N/04° 20' 42"E	48.00 m
Nordsø A-1	55° 24' 20"N/05° 24' 21"E	44.00 m
Nordsø A-2	55° 24' 21"N/05° 03' 34"E	44.00 m
Belgian sector		
BH 89/I	51° 44' 20"N/02° 32' 00"E	37.00 m

Table 6 Correlation of The Netherlands/British Middle and Early Pleistocene chronostratigraphy (after Gibbard et al., 1991)

The Netherlands			Great Britain
Holsteinian		←——→	Hoxnian
Elsterian		←——→	Anglian
Cromerian	Interglacial IV		
	Glacial C	←······	
	Interglacial III		
	Clacial B	······→	Cromerian (s.s.)
	Interglacial II		
	Glacial A	←······	
	Interglacial I		
Bavelian	Leerdam Interglacial		
	Bavel Interglacial		
Menapian			
Waalian	C		
	B		
	A		
Eburonian			
			Beestonian (p.p.)
	C5-6	←——→	Pastonian
	C4c		Pre-pastonian/Baventian
Tiglian	C1-4b	←——→	Bramertonian/Antian
	B		Thurnian
	A	←- - -→	Ludhamian
Praetiglien		←- - -→	Pre-Ludhamian

←——→	correlation highly probable
←- - -→	correlation probable
←······→	correlation not precise

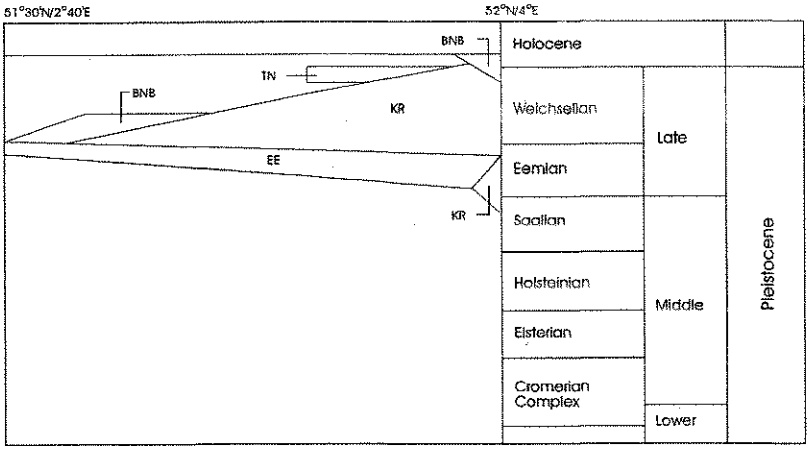
Table 7 Suggested correlation of the Middle and Late Pleistocene Stages in Britain and The Netherlands (after Jeffery et al., 1989)

Britain			The Netherlands
Holocene			Holocene
PLEISTOCENE	LATE	Devensian	Weichselian
		Ipswichian	Eemian
	MIDDLE	Saalian "Wolstonian"	Saalian
		Hoxnian	Holsteinian
		Anglian/ "Wolstonian"	Elsterian

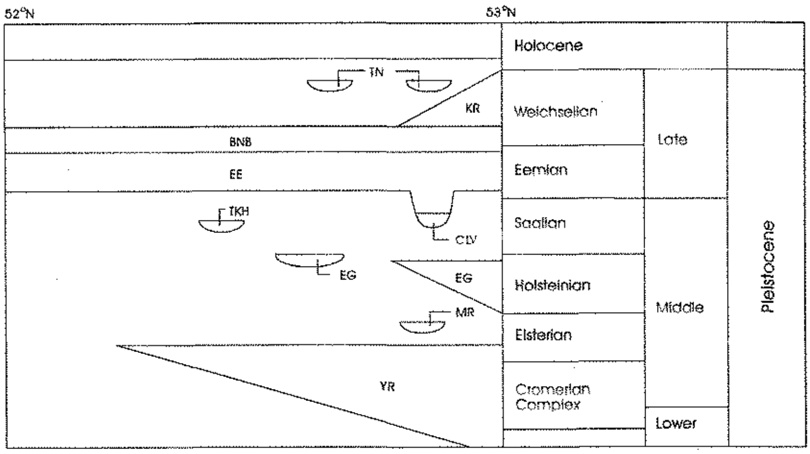
Table 8 Detailed chronostratigraphy of the Weichselian Stage (after Mörner 1970; Zagwijn & Van Staalduinen, 1975; Koster, 1988) (Not to scale)

Chronostratigraphy		^{14}C years
		10.000
Late Weichselian	Late Dryas Stadial	11.000
	Allerød Interstadial	11.800
	Early Dryas Stadial	12.000
	Bølling Interstadial	13.000
	Earliest Dryas Stadial	14.000
Middle Weichselian (Pleniglacial)		23.000
		29.000
	Denekamp Interstadial	32.000
		37.000
	Hengelo Interstadial	39.000
		43.000
	Moershoofd Interstadial	50.000
Early Weichselian	Odderade Interstadial	ca. 58.000
	Brørup Interstadial	ca. 65.000
	Amersfoort Interstadial	ca. 68.000
		ca. 110.000

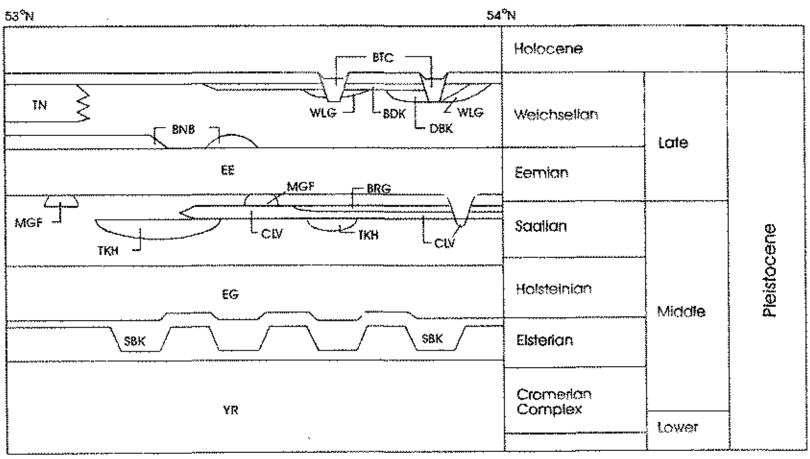
Tabel 9 Schematic relationship formations between 51°30' - 52° N



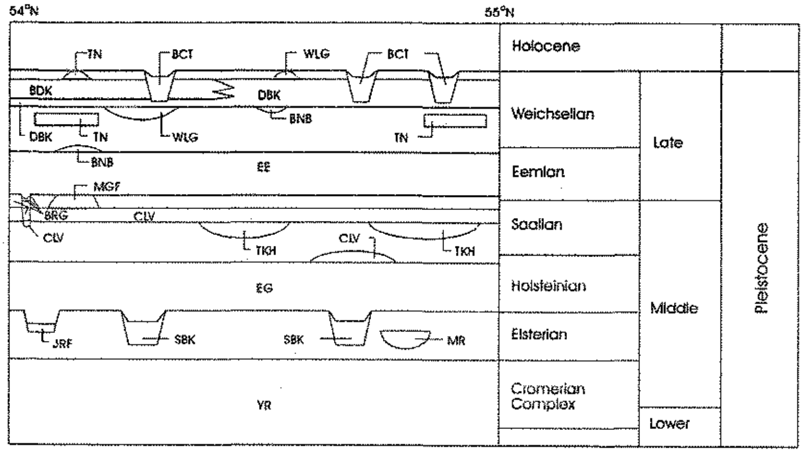
Tabel 10 Schematic relationship formations between 52° - 53° N.



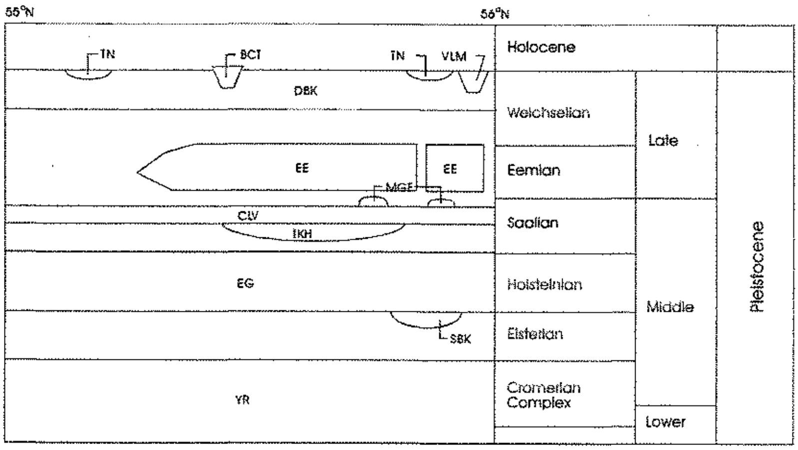
Tabel 11 Schematic relationship formations between 53° - 54° N



Tabel 12 Schematic relationship formations between 54° - 55° N



Tabel 13 Schematic relationship formations between 55° - 56° N



TN	Twente Formation	MGF	Molengat Formation
KR	Kreftenheije Formation	BRG	Borkumriff Formation
BCT	Botney Cut Formation	CLV	Cleaver Bank Formation
VLM	Dogger Bank Formation, Volans Member	TKH	Tea Kettle Hole Formation
BDK	Bolders Bank Formation	EG	Egmond Ground Formation
DBK	Dogger Bank Formation	JRF	Juister Riff Formation
WLG	Well Ground Formation	SBK	Swarte Bank Formation
BNB	Brown Bank Formation	MRF	Middelrug Formation
EE	Eem Formation	YR	Yarmouth Roads Formation